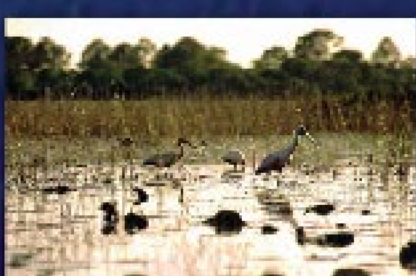
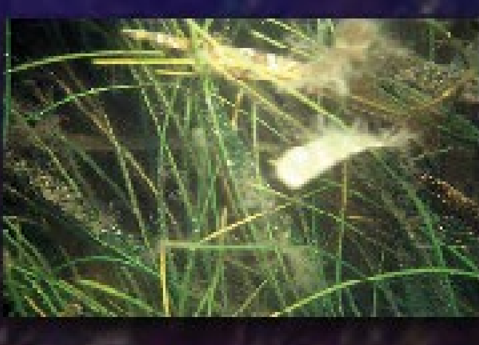
An Assessment of Coastal Hypoxia and Eutrophication in U.S. Waters





November 2003

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To obtain additional information regarding the CENR, contact the CENR executive secretariat at (202) 482-5921.

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National Science and Technology Council
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Executive Summary

The activities undertaken to develop this Assessment have been conducted under the auspices of the National Science and Technology Council's Committee on Environment and Natural Resources (CENR). The report responds to a call by Congress for an "Assessment of Hypoxia" as described in the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 ("HABHRCA," Title VI of P.L. 105 383, section 604(b)). The Assessment examines "the ecological and economic consequences of hypoxia in United States coastal waters; alternatives for reducing, mitigating, and controlling hypoxia; and the social and economic costs and benefits of such alternatives." Congress passed this legislation in the face of increasing frequency and intensity of outbreaks of harmful algal blooms (HABs). The Assessment further supports initial Congressional findings that a significant factor causing or contributing to HABs may include excessive nutrients in coastal waters and that HABs and blooms of non-toxic algal species may also lead to other damaging marine conditions, such as hypoxia (reduced oxygen concentrations), which are harmful or fatal to fish, shellfish, and benthic organisms.

Definitions of Hypoxia and Eutrophication

In aquatic ecosystems, hypoxia refers to a depletion of the concentration of dissolved oxygen in the water column from what can be near 9 mg/L (roughly the maximum solubility of oxygen in estuarine water on an average summer day), to below 2 mg/L. If hypoxic conditions are reached, these local, atypically low oxygen conditions can profoundly affect the health of an ecosystem and cause physiological stress, and even death, to associated aquatic organisms. While hypoxia can occur naturally, periodically both hypoxia, and the more extreme condition of anoxia (a total loss of dissolved oxygen), may indicate a stressed environment resulting from a systemic problem of an overabundance of nutrients (i.e., eutrophic conditions). Eutrophication is defined as an increase in the rate of supply of organic matter to an ecosystem (Nixon 1995). An increase in the rate of supply of organic matter is either from external sources or from production within the system through biological processes stimulated by increased nutrients. Increased organic matter and, more specifically, nutrient inputs can lead to a variety of deleterious effects, including overgrowth of aquatic plants like dense nuisance and toxic algal blooms. Aquatic plants rapidly increase in abundance by uptaking these excess nutrients and, through photosynthesis, convert this matter into energy. When these plants die, their organic material sinks to bottom waters and is decomposed by microbes (e.g., bacteria), consuming oxygen in the process, which may lead to hypoxia, and in extreme cases, anoxia.

Causes of Hypoxia and Eutrophication

Population growth and related activities, such as urban runoff, agriculture, wastewater treatment, and burning of fossil fuels, have dramatically increased nutrient inputs to receiving waters over natural levels. While phosphorous cannot be ignored, nitrogen is most frequently the common driver of estuarine eutrophic conditions and currently comes mostly from non-point sources. The growing population increases the activities that can contribute to introducing nitrogen into streams and, therefore, into estuaries. The major sources come from three general categories:

- Agricultural: Sources include leaching and runoff from fertilized lands and animal waste. Agriculture is the largest source of nitrogen pollution to coastal waters.
- Urban and suburban: Sources include point sources from municipal and industrial treatment plants and non-point sources from septic systems, storm sewers, and lawn and landscape runoff.

- Atmospheric: Sources include oxidized nitrogen emissions (NO_x) generated by fossil fuel combustion and subsequent deposition onto the landscape.

The amount of nitrogen produced by each of these source categories is dependent on a variety of local and regional factors, including rainfall patterns, soil composition, waste treatment methods, and land-use practices, to name only a few. The rate of these inputs can also be altered by factors that include climate change and variability, precipitation patterns, and upstream land use. To summarize, local and regional factors, in combination with climate change and variability and human resource use, make it difficult to analyze the problem and prevent simple solutions.

Further, individual estuaries differ in their susceptibility to eutrophication and hypoxia. Water volume and depth, freshwater inflow, and tidal exchange can all determine how well an estuary responds to increased nutrient fluxes and how able it is to resist the negative effects of eutrophication. Changes in climate may also affect estuary susceptibility. A complete understanding of the factors that determine estuary response does not exist and, therefore no robust scheme exists to classify estuaries based on their susceptibility.

Impacts and Effects

There are a wide range of potential negative effects resulting from eutrophication, and possible subsequent hypoxia, on the health, and goods and services provided directly and indirectly by coastal ecosystems. Some effects include:

- Decreased light availability, algal dominance changes, and increased organic matter production. These primary symptoms can further lead to degradation of habitat, altered migration patterns, decreased fishery production, and subsequent economic impacts on industries dependent on ecosystem productivity.
- Decreases in swimming, boating, and tourism due to excessive and unsightly blooms of algae. Alterations in these recreational and commercial activities can impact coastal communities vitally dependent on delivery of such ecosystem goods and services.
- Nutrient-induced increases in abundance and growth of toxic algae. Associated algal toxins can result in either human and wildlife illness or death if contaminated seafood is consumed or if wind-borne toxins are inhaled.
- Anoxia-induced shifts in biogeochemical reactions, such as reduction of sulfate to sulfide in bottom sediments, resulting in release of hydrogen sulfide. Although the chemosynthetic process turns hydrogen sulfide into a food source for some bacteria, it is toxic to most forms of marine life.

Status and Trends

In 1999, NOAA completed a comprehensive assessment of the scale, scope, and characteristics of nutrient enrichment and eutrophic conditions in 139 U.S. estuaries using the best available information and expert opinion from academic, state, local, and Federal scientists (Bricker et al.). This is the most comprehensive evaluation of coastal eutrophication to-date, yet is largely qualitative, as trend data are scarce and gaps in data and information exist. Approaches to filling these gaps are discussed in the Recommendations section.

As hypoxic events are becoming increasingly visible, greater incidences of hypoxia/anoxia, as well as primary symptoms of eutrophication (e.g., macroalgal blooms), have been recorded in a significant number of the Nation's estuaries. High overall levels of eutrophic conditions (i.e., symptoms generally occur periodically and/or over extensive areas as determined by concentration level, spatial coverage, and occurrence of chlorophyll *a*, epiphytes, macroalgae, dissolved oxygen, submerged aquatic vegetation, and nuisance/toxic algal blooms) occur in 44 of 139 estuaries examined, with an additional 40 exhibiting moderate levels. Anoxia is observed at some time during the year in one third of the Nation's estuaries; hypoxia and biologically stressful oxygen concentrations in more than half.

More information is needed to determine the full spatial extent and whether incidence of hypoxia is increasing or decreasing, but a cursory review of peer-reviewed literature suggests that between 1970 and 1995 more individual estuaries developed eutrophic conditions, or symptoms became more pronounced, than those where conditions and symptoms were in decline. Nationally, the reverse was true for dissolved oxygen levels. This illustrates the importance of individual assessments of susceptibility, characteristics, nutrient sources, and mitigation strategies for each estuary.

Mitigation Strategies

Strategies to combat the negative effects of eutrophication and hypoxia must focus on reducing nutrient loads from all major sources. Because a large proportion of these nutrients comes from non-point sources, mitigation strategies must be comprehensive and involve those affected by these actions. Among the actions that can reduce nutrient inputs (by source category) are:

- Urban and Suburban
  - Lessening nutrient inputs to storm sewers and sewer overflows
  - Decreasing fertilizer application and runoff from lawn and landscape care
  - Promoting proper disposal of pet and wildlife waste
  - Reducing nutrient discharges from municipal and industrial water treatment plants

- Agricultural
  - Decreasing fertilizer application rates and optimizing its use
  - Encouraging alternate tilling methods and cropping systems
  - Improving treatment and disposal of animal waste
  - Promoting the use of conservation buffers (e.g., field borders, riparian zones, wetlands, and other areas particularly effective at trapping nitrogen) and other physical mechanisms to decrease direct agricultural runoff to water bodies

- Atmospheric sources
  - Cooperatively applying air quality provisions regionally
  - Increasing fuel efficiency of combustion engines
  - Considering the dispersal patterns of atmospheric discharges from power plants and other industrial sources
  - Using alternative power sources with lower NO_x emissions
  - Decreasing NO_x emissions

As small areas or strips of land in permanent vegetation, such as field borders, grassed waterways, riparian zones, and wetlands, slow water runoff and stabilize riparian areas, they effectively mitigate the movement of sediment, nutrients, and pesticides within farm fields, lawns, and the like. Sometimes referred to as 'sinks' for this filtering capacity, nitrogen loads can also be reduced through restoring these damaged systems or preserving existing features. In addition to their role in reducing nutrient loads, these areas also provide recreational and ecological benefits.

Recommendations

All recommended programs and activities are subject to the availability of resources.

Watersheds and Adaptive Management

Coastal nutrient problems are most often driven by activities in the watersheds and airsheds. To develop an effective national strategy to reduce nitrogen pollution in coastal waters, Federal agencies should display leadership on issues that span multiple jurisdictions, involve several sectors of the economy, threaten Federally managed resources, or require broad expertise or long-term effort beyond the resources of local and state agencies. Watershed and adaptive management approaches should be adopted for maximum success in reducing nitrogen pollution effects.

Watershed Approaches. A watershed approach uses hydrologically defined areas to coordinate the management of water resources. This is advantageous, because all activities within a landscape that affect watershed health are taken into consideration. It provides a framework to consider a number of needs that are usually looked at singularly: water quantity and quality, flood control, navigation, fisheries, biodiversity, habitat preservation, recreation, and agriculture. A nationwide strategy to reduce nutrient loads should include critical roles for local watershed and coastal managers, in addition to the roles for Federal and state governments.

The focus for any management program should be to reduce nitrogen inputs at their source. It is essential that local, state, and Federal governments work together and with the private sector, universities, and local citizens. The goals should be to reduce the number of coastal water bodies demonstrating severe eutrophication impacts and ensuring that no coastal areas now ranked as 'healthy' (showing no or low/infrequent nutrient-related symptoms) develop nutrient-related, over-enrichment problems. Local and state agencies have greater familiarity with nutrient sources and related water quality problems and their efforts should be coordinated with Federal activities to:

- Facilitate accessibility of data, information, and expertise;
- Improve monitoring capabilities;
- Undertake periodic assessment of coastal ecosystem conditions;
- Determine vulnerability of coastal ecosystems to hypoxia;
- Focus research; and
- Measure progress against annual and long-term performance measures indicative of water quality and overall ecosystem health.

Adaptive Management. The complex nature of nutrient cycling and transport within watersheds, in hand with the complex physical, chemical, and biological dynamics of estuarine and coastal systems, makes it difficult to predict estuarine responses to actions on land, including responses to management actions. Management plans should provide an adaptive framework of reanalysis and adjustment as more information becomes available. To be most effective, the program should include comprehensive monitoring, interpretation, modeling, and research designed to:

- Detect environmental trends to evaluate the effectiveness of management actions;
- Observe physical, chemical, and biological processes and their roles in the cause-and-effect relationship between nutrient inputs and water quality;
- Separate trends caused by changes in climate, streamflow, and nutrient and landscape management measures;
- Evaluate transport and transformation of nutrients from natural, urban, and agricultural landscapes to ground and surface waters;
- Estimate inputs and outputs of nutrients, as well as the biogeochemical cycling and water quality effects of those nutrients; and
- Examine oceanographic and climate influences on impacts on estuarine productivity.

Reducing Uncertainties

The highest levels of confidence in assessing eutrophic conditions and trends are for systems with moderate or high levels of eutrophication, because they are well-studied. For many other systems, data and information available for assessment are uncertain, at best, and insufficient for analysis, at worst. A comprehensive monitoring, research, and modeling program, coupled interactively with the development of predictive models, is needed to provide information with a high level of certainty for adaptive management strategies and to assure the success of implemented actions. There are four principal research areas associated with the study and management of coastal eutrophication, each with priority research needs for reducing uncertainties.

Impacted and Susceptible Coastal Waters. A classification scheme to enable managers to understand the susceptibility of a given estuary to nutrient over-enrichment needs to be developed. With such tools, management, monitoring, and research efforts could be focused on restoring and protecting those coastal ecosystems that are likely to be most severely impacted by increasing nutrient inputs.

Any research efforts should include investigations to better understand 'bottom-up' control of nutrient enrichment. This is necessary to estimate the societal and economic costs of eutrophication. The program should also include study of 'top-down' control, which could lead to better management of nutrient pollution.

A monitoring and research program should provide the data needed to better understand changes in biogeochemical cycles caused by the onset of, and recovery from, eutrophication. This understanding is essential for making sound policy and management decisions about protection and restoration of the Nation's estuarine resources.

Watersheds Draining Into Impacted and Susceptible Coastal Waters. Assessment of surface and groundwater, riparian zones, and wetlands within the watershed as sources, sinks, conveyors, and transformers of nutrients is necessary for the best management of coastal nutrient pollution. To date, few studies have examined all inputs and outputs of nitrogen to riparian zones and wetlands. Research should be conducted in the context of whole watersheds and should include the effects of climate variability and change on sink effectiveness.

Identifying and quantifying nutrient inputs and determining the fate of nutrients under different land-use scenarios is critical to managing nutrient pollution. For most systems, the amount of nutrients delivered from non-point sources is larger than those from point sources, but knowledge of all the sources of non-point discharges, particularly from the atmosphere, and their percentage contribution to overall nutrient loads is meager. There is an urgent need to better understand these non-point sources.

Another critical piece of information needed to effectively manage nutrient pollution is the understanding of nitrogen retention in the landscape, which may be affected by land-use history. Approaches are needed to evaluate the retention and fate of nitrogen deposition, particularly in suburban areas and landscapes with mixed land-use, and how these may change with changes in climate.

Predictive Modeling of the Watershed-Coastal System. Models to estimate sources and fates of nutrient inputs to watersheds and coastal ecosystems are critical tools for resource managers. Many models exist, but most have not been validated or verified with independent data or do not include all major source inputs. Further, most models are site specific. A goal should be to develop a comprehensive, quantitative understanding of nitrogen cycling and transport in variable-sized landscapes to improve and validate models of sources and fluxes of nitrogen through the watershed to coastal waters. Modeling efforts should include both hindcasting and forecasting exercises and the capability of assimilating information on changes in policies and practices.

The development of more sophisticated models, and those that apply to a range of coastal ecosystems, would help integrate scientific understanding of nutrient enrichment and highlight key uncertainties. Models should aid managers in setting goals for protecting and restoring coastal ecosystems and for understanding how nutrient pollution interacts with other stressors, but must also first be tested, calibrated, and validated before they become the tools of managers.

Strategies for Management of Impacted and Susceptible Coastal Ecosystems. Management efforts would be enhanced by a clearer definition of Society's goals for desirable uses and services provided by these ecosystems and translation of those desires into scientifically measurable goals that can serve as the basis of ecosystem management. Appropriate indicators of nutrient pollution should be developed that can be directly related to societal goals, and in turn, related to nutrient loads, so that specific targets for nutrient reduction can be set.

At present, there are a variety of approaches for reducing nutrient sources. These include voluntary approaches, approaches based on subsidies and financial incentives, technology-based regulation, assessing fees or taxes that are based on permissible loading levels, and implementing marketable permits for achieving permissible loading levels. Optimal policy and management strategies to maximize the benefits and minimize the costs of nutrient reduction should be developed.

A variety of approaches also exist for reducing nutrient loads in coastal ecosystems. Many of these technologies and management practices address phosphorus pollution, however, and must be altered to address nitrogen pollution. Research on, and development of, innovative technologies, such as constructed wetlands, and independent assessment of these technologies is needed. Once working, results at smaller scales should be modified to fit larger watersheds.

The Role of Federal Agencies

A coordinated plan of action to monitor, understand, and manage coastal eutrophication will require Federal leadership and oversight, because watersheds cover multiple jurisdictions and Federally-managed resources. A framework for interagency communication, coordination, and cooperation must be developed to avoid duplication of effort and incompatibilities of research and management objectives and to ensure that important problems are dealt with even though they may not fit neatly under one agency's jurisdiction. A multi-agency program should be developed to link monitoring, research, modeling, education, and adaptive management capabilities at the Federal level. Additionally, the multi-agency framework should include approaches for identifying opportunities to take advantage of and, where appropriate, augment existing monitoring programs at both the federal and state levels. However, all of these activities will have to be considered in light of budget constraints and agency priorities.

Presently, the President of the United States coordinates science, space, and technology across the many Federal research and development programs through the National Science and Technology Council. The Council's Committee on Environment and National Resources includes several Federal agencies involved in addressing hypoxia and eutrophication. These members will provide the oversight necessary to avoid duplication of Federal efforts in the areas of science and technology research and development. A coordinated Federal effort is needed to monitor, study, and manage impacted and endangered coastal waters and their associated watersheds.

The Future

Any response to the ecological and economic dangers of eutrophication and hypoxia must include continued research and monitoring. These include research on the characteristics that govern estuary susceptibility and adaptability, the factors that determine nutrient loading from various land areas, the quantification of economic and social impacts of nutrient pollution, the development of better monitoring systems, the evaluation of existing mitigation strategy effectiveness, and the development of new mitigation strategies.

Response strategies should be undertaken through an adaptive management structure, focused on watersheds and based on comprehensive site-specific and national monitoring and assessments. Such an approach should be focused on protecting healthy ecosystems and restoring those that have been damaged, rather than a national goal of nitrogen reduction per se. This approach requires active participation of state, local, and regional managers leveraged by support and coordination from the Federal government.

Introduction

The Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (HABHRCA; P.L. 105-383) recognized that human activities contribute to the impairments caused by harmful algal blooms (HABs) and hypoxia within the watersheds of our Nation's estuarine and coastal waters. To facilitate an enhanced national effort to address these problems, the statute called for national assessments of the causes and consequences of HABs and of coastal hypoxia, in addition to a region-specific assessment of the causes and consequences of hypoxia in the northern Gulf of Mexico and an Action Plan to address those Gulf-specific problems. The harmful algal bloom and Gulf assessments (CENR 2000a, b), as well as the Action Plan (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001), have been delivered to Congress. This report fulfills the final requirement outlined in Section 603 (c) of the HABHRCA calling for an assessment which:

- Examines the ecological and economic consequences of hypoxia in United States coastal waters;
- Provides alternatives for reducing, mitigating, and controlling hypoxia;
- Evaluates the social and economic costs and benefits of such alternatives;
- Establishes needs, priorities, and guidelines for a peer-reviewed, interagency research program on the causes, characteristics, and impacts of hypoxia;
- Identifies alternatives for preventing unnecessary duplication of effort among Federal agencies and departments with respect to hypoxia; and
- Provides for Federal cooperation and coordination with, and assistance to, the States, Indian tribes, and local governments in the prevention, reduction, management, mitigation, and control of hypoxia and its environmental impacts.

Keeping Eutrophication in Perspective

At least five major attributes of coastal ecosystems are affected by stressors that can result in changes in the condition and use of the Nation's coastal waters – water quality, sediment quality, habitat quality, biotic quality and human use. Hypoxia and eutrophication are two major stressors (some would contend the major stressors) of water quality and contributors to degradation of sediments, habitats, biota, and use. While very important, hypoxia and eutrophication are not the only stressors that need to be addressed in order to protect and restore the Nation's coastal waters. Chemical contamination and toxicity, habitat loss, and excessive use all contribute to the degradation of the ecological condition of coastal waters. This report focuses only on one of the primary stressors – coastal eutrophication – and one of its primary results – coastal hypoxia.

Definitions of Hypoxia and Eutrophication

In aquatic ecosystems, hypoxia refers to an oxygen deficiency, typically in bottom waters, which can cause physiological stress and, occasionally, death to aquatic organisms. Anoxia, a more extreme condition, refers to a total lack of oxygen. Hypoxia can occur naturally, but more often it indicates a stressed environment as it results from an excess of decomposing organic matter in bottom waters. Thus, hypoxia and anoxia are key indicators of the health of an aquatic ecosystem. Yet, dissolved oxygen is only one of six symptoms used to track the effects of a more systemic problem – coastal eutrophication.

Eutrophication is defined as an increase in the rate of supply of organic matter in an ecosystem (Nixon 1995). An increase in the rate of supply of organic matter comes from external sources or production within the system through biological processes stimulated by increased nutrients. Externally-supplied organic matter most often comes from wetlands or uplands via river water. Internally-produced organic carbon comes from algae growth stimulated by available nutrients. This organic matter supply has both positive and negative consequences. While organic matter is the basic 'fuel' of the coastal and marine food webs that support rich and diverse commercial and recreational fisheries, an over-supply can produce undesirable effects.

When high levels of nutrients over-stimulate the production of planktonic algae (floating), epiphytic algae (those attached to surfaces), and macrophytes (sea weeds), dense nuisance and toxic blooms can develop, resulting in decreased light penetration, loss of beneficial submerged aquatic vegetation (SAV), over-production of organic matter, and ensuing secondary symptoms as described in Box 1. In addition, algae that are not incorporated into the food web (via consumption by zooplankton), fecal products or other debris from zooplankton feeding on algae, and externally supplied particulate organic matter sink into bottom waters as "excess" organic matter (Figure 1). Decomposition of this

BOX 1 – SYMPTOMS OF EUTROPHICATION

Primary Symptoms

High Levels of Chlorophyll a – Chlorophyll *a* (that pigment that makes plants green) is a measure used to indicate the amount of microscopic algae, called phytoplankton, growing in a water body. High concentrations of chlorophyll *a* indicate problems related to the over production of algae.

Increases in Epiphytic Algae – Epiphytes are algae that grow on surfaces of plants or other objects. If too dense, they can cause losses of submerged aquatic vegetation (SAV) by covering leaf surfaces, thereby reducing light to the plant leaves.

Macroalgae Blooms – Macroalgae are large algae, commonly referred to as "sea weeds." Blooms block sunlight, killing SAV. Additionally, blooms may also smother immobile shellfish, corals, or other habitat. Some blooms can be unsightly and can impact tourism due to declining value of swimming, fishing, and boating opportunities.

Secondary Symptoms

Low Dissolved Oxygen – This includes hypoxia and anoxia, and may occur when large algal blooms sink to the bottom, consuming oxygen during decay or respiration. Low dissolved oxygen can cause fish kills, habitat loss, and degraded aesthetic values, resulting in loss of tourism.

Loss of Submerged Aquatic Vegetation – This is from decreased light and poor water clarity associated with overgrowth of algae. It can also be a result of epiphytic algae growth on leaves. Losses of grasses can have negative impacts on some fisheries, because the grass beds serve as important habitat.

Algal Blooms – While some algal blooms are naturally occurring, many times nuisance and toxic algal blooms are caused by a change in the natural mixture of nutrients. The change is often associated with a long-term increase of nutrients. Noxious blooms may release toxins that kill fish and shellfish. There are also human health problems related to consumption of fish and shellfish that have accumulated algal toxins and from toxins that become airborne and are inhaled.

(Adapted from Bricker et al. 1999)

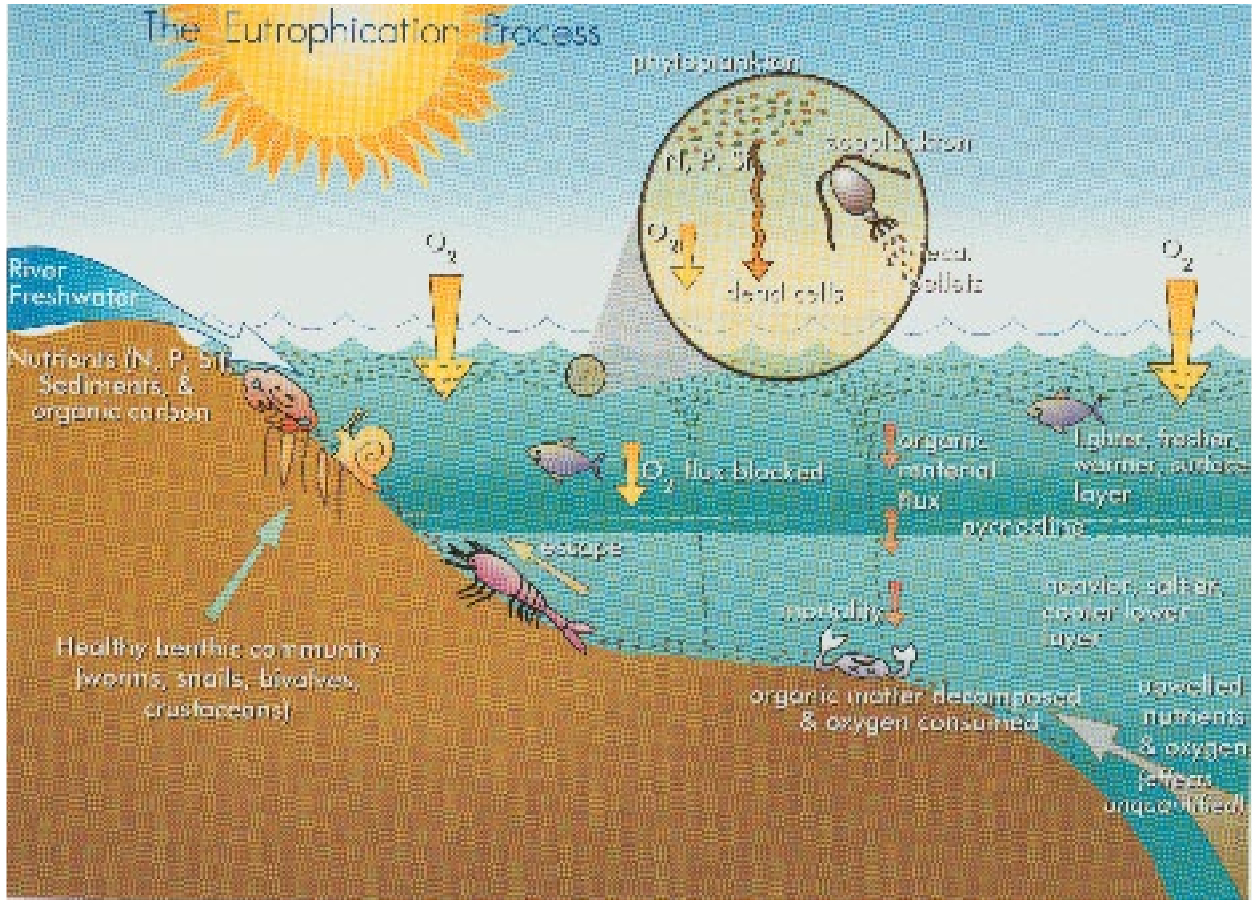


Figure 1*. The Eutrophication Process. Eutrophication occurs when organic matter increases in an ecosystem through nutrient stimulated algal growth or through inputs of organic matter from other sources. (Adapted from CENR 2000a)*

material by bacteria and other organisms consumes oxygen, and when the consumption rate is faster than its replenishment, oxygen concentrations decrease. In many saltwater systems, the layering of warmer and/or less saline waters over colder and/or saltier bottom waters inhibits mixing and reduces the resupply of oxygen from the surface to replenish deficits created by the decomposing organic matter in deeper water resulting in hypoxic or anoxic bottom waters. Thus, reducing or reversing the effects of eutrophication requires understanding the relative roles of externally-supplied and internally-produced organic matter.

These symptoms of eutrophication have a wide range of impacts on the use of coastal ecosystems (Figure 2). Excessive and unsightly algal blooms can negatively impact boating, swimming, and tourism. In addition, the loss of SAV and the presence of low dissolved oxygen can significantly degrade habitats for fish and other commercially and ecologically important organisms. Other less obvious impacts include changes in the phytoplankton community structure as a result of changes in ratios of key plant nutrients (i.e., nitrogen, phosphorus, and silicon). These changes can result in food webs that are less efficient in supporting key fisheries and favor algal blooms, including those toxic to fish, marine mammals, birds, and people. Serious illness and death may result from consuming fish and shellfish contaminated with algal toxins or from direct exposure to water or airborne toxins during blooms.

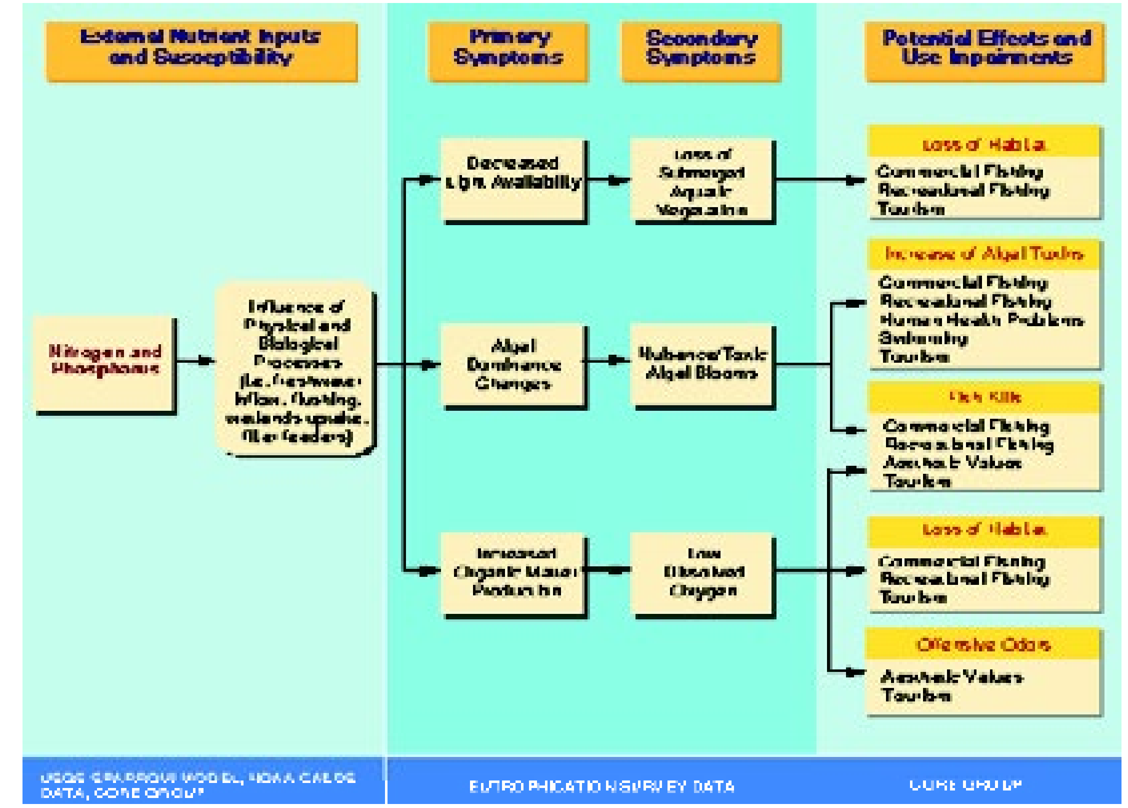


Figure 2*. Eutrophication Model. Note that low dissolved oxygen is not a direct response to nutrient inputs but rather is a symptom that follows a progression that begins with nutrient inputs. The direct response is elevated algal production (the first indication that there may be a problem with nutrient enrichment) that may cause low dissolved oxygen conditions in bottom waters. Note also that there are other symptoms, loss of Submerged Aquatic Vegetation (SAV), and occurrences of nuisance and toxic algal blooms, which indicate a more advanced nutrient enrichment problem. (Adapted from Bricker et al. 1999)*

Causes of Coastal Eutrophication

In the Introduction, eutrophication is defined as an increase in the rate of supply of organic matter, and that this increase comes from both allochthonous (external) inputs and autochthonous (internal) production. Natural allochthonous sources include river-borne phytoplankton, organic detritus, and marginal vegetation, supplemented considerably by anthropogenic point sources that include sewage and some industrial effluents. Natural autochthonous sources include phytoplankton, macroalgae, and aquatic organism feces. The increase in loads of nutrients (nitrogen and phosphorus) to the marine environment stimulates the production of autochthonous organic matter, principally in the form of phytoplankton and macroalgae.

The NOAA estuarine eutrophication assessment (Bricker et al. 1999) reports that nitrogen is the most common driver of estuarine eutrophication, with non-point sources of nitrogen accounting for more than 75 percent of the total nitrogen input to the 44 estuaries surveyed and determined to have high eutrophic conditions. Agricultural sources accounted for more than 50 percent of non-point inputs in 17 of these 44 estuaries; urban sources accounted for more than 50 percent of the non-point source contribution for seven estuaries. This is consistent with the 305(b) reports from the States that the leading cause of poor water quality is polluted runoff, and that agriculture affects 70 percent of affected rivers and streams.

The following discussions outline three major sources contributing to nutrient loading, particularly of nitrogen, to estuaries: urban and suburban sources, agricultural sources, and atmospheric loads.

Nutrient Sources

Urban and Suburban Sources

Urban and suburban sources include point sources from municipal and industrial treatment plants and non-point sources from septic systems, storm sewers and combined sewer overflows (CSOs), and lawn and landscape care. While non-point sources dominate the nitrogen input to most coastal waters of the United States, sewage and other urban sources are significant in many coastal rivers and bays. They are the largest inputs in Long Island Sound, Hudson River estuary, Boston Harbor, Raritan Bay, and South San Francisco Bay (NRC 1993a, 2000).

Municipal wastewater treatment plants are the primary point source discharge of nutrients to waterways in the United States, though industrial sources are also significant in some basins. In the 1990s, most sewage in the United States received secondary treatment, designed to lower the discharge of labile organic matter that contributes to 'biological oxygen demand' (NRC 2000). While human wastes are the primary urban source of nitrogen, atmospheric deposition of nitrogen from fossil fuel combustion can also be substantial (see discussion on Atmospheric Sources). Most oxidized nitrogen emissions (NOx) are deposited close to the emission source, impacting urban areas (NRC 2000; Howarth et al. 2002b, 2002c).

In older United States cities, sanitary wastes and stormwaters are served by the same combined sewer system. Consequently, some of the nitrogen entering sewage treatment plants originates from fossil fuel sources and from lawn fertilizer washed off streets and lawns in rainstorms (NRC 2000). Most of the time, all of the combined sewage and stormwater goes to a sewage treatment plant, but heavy rains may cause pipes to fill and induce overflows and outfalls into coastal waters. The nitrogen inputs from storm sewers and CSOs are not well quantified for any major urban area, but they are probably less than the input from sewage effluent (NRC 1993a, 2000). A rough estimate for the Hudson River estuary suggests that nitrogen inputs from CSOs and storm sewers in the New York metropolitan area are ten percent of the sewage input (Howarth et al. 2002c).

Approximately 25 percent of the population of the United States and approximately 37 percent of new development, is served by septic systems (i.e., onsite/decentralized wastewater treatment systems, or OWTSs) rather than by sewers (EPA 1997; NRC 1993a). In some coastal areas, septic systems are the primary source of nitrogen to coastal waters. A well-designed and maintained septic system is effective for containing pathogens and phosphorus, but because of the greater mobility of nitrogen in soils, they are generally not effective at removing nitrogen (NRC 2000). The Environmental Protection Agency (EPA) estimates that on a national basis anywhere from 10 to 20 percent of onsite systems are failing annually (EPA 1997).

A variety of other activities by homeowners and urban residents can generate nutrient pollution. In particular, garden and lawn care activities can result in significant inputs of nitrogen to area waterways by non-point source pathways, such as runoff.

Agricultural Sources

Agricultural sources of nutrients come from leaching and runoff from agricultural lands and from animal agriculture. Agricultural fertilizer use in the United States grew rapidly from 1961 until 1980, declined somewhat after 1980, and has been rising steadily since 1985 (NRC 2000; Howarth et al. 2002a).

Since 1961, total new nitrogen inputs to agricultural fields in the United States (including nitrogen fixation by legumes) have doubled from eight million metric tons per year in 1961 to 17 million metric tons per year in 1997 (Howarth et al. 2002a). Though variability is great, on average, about 20 percent of the nitrogen applied to agricultural fields leaches into surface or groundwater (NRC 1993b; Howarth et al. 1996, 2002a), ranging from a leaching loss as low as three percent for grasslands with clay-loam soils to as high as 80 percent for some row-crop fields on sandy soils (Howarth et al. 1996). Climate is also important; nitrogen losses are greater in areas of high rainfall and in wet years. These differences indicate that great strides in reducing nitrogen pollution to aquatic ecosystems can be obtained by targeting the particularly 'leaky' agricultural fields.

Certain agricultural management practices, such as tile drainage, can accelerate the loss of nitrogen from agricultural lands to streams. More than 200,000 square kilometers (50 million acres) of land has been drained in the upper Mississippi River Basin (MRB) (Goolsby et al. 1999) to lower the water table to make the land suitable for farming. This 'short circuits' the flow of groundwater by draining the top of the water table into underground drainage tile lines and ditches. It also promotes the conversion of organic nitrogen and ammonia, which are relatively immobile forms of nitrogen, into nitrate, which is very mobile. The drained water, which may contain high concentrations of nitrate (Zucker and Brown 1998b), flows into nearby streams, the Mississippi River, and eventually into the Gulf of Mexico where it contributes to eutrophication and hypoxia (Rabalais 2002).

Animal wastes, particularly from large feeding operations, contribute significantly to the level of nitrogen in coastal waters, and the production of animal protein continues to increase, in part driven by

a steady increase in the per capita meat consumption of Americans (Howarth et al. 2002a). The trend to concentrate meat production facilities also continues. During the 1990s, production of hogs, dairy cows, poultry, and beef cattle all rose, while the number of operations declined (NRC 2000). That is, more protein was produced by fewer but larger operations. Wastes from concentrated animal feeding operations (CAFOs) tend to be handled in one of two ways: they are spread onto agricultural fields, or they are held in lagoons. Some operations are also beginning to compost animal wastes (NRC 2000).

Animal manure can be considered a fertilizer, and recycling of this organic waste to agricultural fields, seen as desirable. In practice, however, it is difficult to apply manure with uniformity over a field and also to ensure uniform delivery of nutrients appropriate to crop needs because of the variability of nutrient release from the applied manure[1] (NRC 2000). Also, since most manure in the United States is transported less than ten miles, it means fields near animal feeding operations can be over fertilized, with concomitant groundwater and downstream aquatic ecosystem pollution (NRC 2000).

Atmospheric Sources

Atmospheric nitrogen emissions come from two major sources: stationary (i.e., power plants) and mobile (i.e., cars, trucks, buses, and other internal combustion engines). Oxidized nitrogen emissions to the atmosphere from fossil fuel combustion contribute 6.9 million metric tons of nitrogen per year to the environment in the United States, roughly 60 percent of the rate of nitrogen fertilizer use in the country (Howarth et al. 2002a). Most of this is deposited onto the landscape during rain showers and as dry deposition.

Oxidized nitrogen emissions are major contributors to acid rain, as well as significant contributors to nutrient pollution in coastal waters. Of the nitrogen deposited onto forests, approximately 20 percent is exported to downstream aquatic ecosystems (NRC 2000; Howarth et al. 2002b). A substantial amount of the nitrogen from fossil fuel sources in the United States (1.3 million metric tons in the late 1990s) is also deposited directly onto the surface waters of the North Atlantic Ocean (Howarth et al. 2002a). Additionally, the atmospheric deposition of nitrogen from fossil fuel combustion is a major input to virtually all of the coastal rivers and bays along the eastern seaboard via export from their watersheds (NRC 2000; Howarth et al. 2002b; Boyer et al. 2002).

Of the major pollutants regulated under the Clean Air Act of 1970 (P.L. 91-604), only NO_x has not declined significantly, although regulation may have stabilized the rate of emissions (NRC 2000). Emissions rose exponentially through the 1960s and 1970s, but have been relatively constant since 1980 (EPA 2000). About half of the emissions came from mobile sources, including automobiles, buses, trucks, and off-road vehicles. Oxidized nitrogen emissions from motor vehicles have increased only 5% since 1970, in spite of an increase of over 140% in total miles traveled annually in the same period (FHWA 2002). Electric power generation produced 42 percent (EPA 2000). As of the late 1990s, the United States produced approximately one third of all the NO_x released from fossil fuel combustion globally.

Geographic Distribution of Sources

Smith and Alexander (2000) recently used the SPARROW model (Smith et al. 1997) to estimate the percentage contribution of five nitrogen sources to the total nitrogen loads exported from 2057 hydrologic units (a part of a watershed) watersheds in the United States. The nitrogen sources were fertilizer, animal agriculture, atmospheric deposition, point sources, and nonagricultural runoff. The geographic distribution of total nitrogen export from four of the nitrogen sources are shown in Figure 3.

[1]Rate of release of nutrients from manure depends on other factors, such as temperature and moisture.

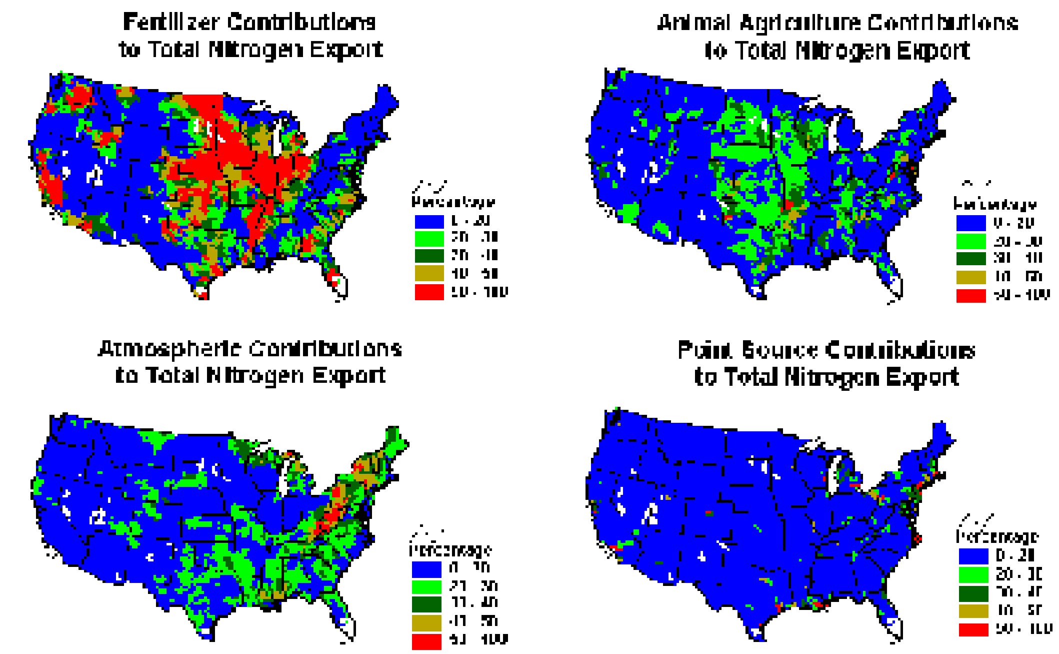


Figure 3. *Percentage contribution from fertilizer, animal agriculture, atmospheric deposition, and point sources to the total nitrogen export from 2057 hydrologic units. (Source: Smith and Alexander 2000; http://water.usgs.gov/nawqa/sparrow/nut_sources/Nutrient_sources_SPARROW.htm)*

Fertilizer was the largest contributor of the total nitrogen exported from hydrologic units in the Central United States (MRB), Southeastern United States, Northwestern United States, and California. It was often the source of more than 50 percent of the total nitrogen exported (note areas in red on maps in Figure 3). Also, it was the predominant source of nitrogen exported from the MRB to the Gulf of Mexico. The largest percentage contribution (20-30 percent) from animal agriculture (i.e., CAFOs, etc.) to total nitrogen export was in the Midwestern United States (MRB) and selected hydrologic units in the Mid-Atlantic and the Northeastern United States. The nitrogen contribution from animal agriculture was almost always less than the contribution from fertilizer, however.

Atmospheric contributions to total nitrogen export were highest in the Northeastern United States. In some hydrologic units it was the largest source of nitrogen, contributing more than 50 percent of the total nitrogen. Nitrogen from atmospheric deposition was also the largest source of nitrogen exported from many hydrologic units in the Southeastern United States and the lower MRB. Municipal and industrial point sources made significant contributions to total nitrogen export in only a few hydrologic units, mostly in the Northeastern United States and along the Louisiana and Texas coasts.

Nitrogen Loads and Yields

Continuous, long-term data on nitrogen loads discharged from rivers to estuaries on the United States coastline do not exist except for a few rivers in the Chesapeake Bay region and the lower Mississippi River. For these rivers, data are available from the United States Geological Survey (USGS) on annual total nitrogen load from the mid-1970s to the present.

Historical data on nitrogen loads and yields for other rivers discharging into the Atlantic, the Gulf, and the Pacific coastal zones were found in various published reports (Boyer et .al 2002; Dunn 1996; Goolsby et al. 1999; Kelly et al. 2001). The data in these reports generally cover various time periods up to about 1993.

Table 1 presents a summary of nitrogen load data from 60 rivers. The table includes the area of the river basin, average annual total nitrogen load[2], average annual total nitrogen yield[3], the period for which the loads were computed, and the source of the data. The nitrogen loads from all sources summarized were computed using the statistical model ESTIMATOR (Cohn et al. 1989). The data are for differing time periods, ranging from five to six years, to more than 20 years. As a result, caution must be used when comparing river basins.

River	Drainage Area (km^2)	Total Nitrogen Load (kg/y)	Total Nitrogen Yield ($kg/km^2/y$)	Period of Record for Nitrogen Loads	Years of Record	Source of Data
Northeast Atlantic Coast						
Charles	475	834	1756	1988-93	6	Boyer et al., 2002
Blackstone	1115	1271	1140	1988-93	6	Boyer et al., 2002
Connecticut	25019	13460	538	1988-93	6	Boyer et al., 2002
Merrimac	12005	5991	499	1988-93	6	Boyer et al., 2002
Androscoggin	8451	3414	404	1988-93	6	Boyer et al., 2002
Saco	3349	1303	389	1988-93	6	Boyer et al., 2002
Kennebec	13994	4660	333	1988-93	6	Boyer et al., 2002
Penobscot	20109	6375	317	1988-93	6	Boyer et al., 2002
Mid-Atlantic Coast						
Schuylkill	4903	8605	1755	1988-93	6	Boyer et al., 2002
Delaware	17560	16875	961	1988-93	6	Boyer et al., 2002
Patuxent	901	855	948	1980-01	24	USGS, 2002
Susquehanna	70189	60776	866	1979-01	23	USGS, 2002
Potomac	30044	24513	816	1979-01	23	USGS, 2002
Mohawk	8935	7103	795	1988-93	6	Boyer et al., 2002
Choptank	293	212	724	1978-01	24	USGS, 2002
Pamunkey	1081	664	614	1990-01	12	USGS, 2002
Rappahannock	4144	2094	505	1989-01	13	USGS, 2002
Hudson	11942	5995	502	1988-93	6	Boyer et al., 2002
James	16213	5207	321	1989-01	13	USGS, 2002
Appomattox	3471	631	182	1990-01	12	USGS, 2002
Mattaponi	1557	266	171	1990-01	12	USGS, 2002
South Atlantic Coast						
Neuse	7024	3099	441	1980-92	13	Harned et al., 1995
Tar	5755	2015	350	1980-92	13	Harned et al., 1995
Nottoway	3732	758	203	1980-92	13	Harned et al., 1995
Roanoke	21948	4073	186	1980-92	13	Harned et al., 1995
Florida Gulf Coast						
Chipola	2023	1406	695	1972-93	21	Dunn, 1996
Alafia	868	543	626	1972-93	21	Dunn, 1996
Manatee	386	231	599	1973-93	21	Dunn, 1996
Myakka	593	278	469	1974-93	20	Dunn, 1996
Peace	3541	1433	405	1973-93	21	Dunn, 1996
Yellow	1616	628	388	1973-93	21	Dunn, 1996
Suwannee	24968	8852	355	1973-88	16	Dunn, 1996
Escambia	9886	3492	353	1973-93	21	Dunn, 1996
Ochlockonee	2953	1025	347	1973-93	21	Dunn, 1996
Apalachicola	44548	15328	344	1974-93	20	Dunn, 1996
Perdido	1020	347	340	1974-93	20	Dunn, 1996
Choctawhatchee	11355	3791	334	1974-93	20	Dunn, 1996
Hillsborough	1632	243	149	1973-93	21	Dunn, 1996
Alabama-Mississippi Gulf Coast						
Tombigbee	47700	24943	523	1974-92	19	Dunn, 1996
Pascagoula	17301	8508	492	1973-93	21	Dunn, 1996
Alabama	56895	20135	354	1973-93	21	Dunn, 1996
Louisiana Gulf Coast						
Amite	3341	3945	1181	1973-85	13	Dunn, 1996
Tangipahoa	1673	1515	905	1976-93	18	Dunn, 1996
Pearl	17024	11610	682	1973-93	21	Dunn, 1996
Bouge Chitto	3142	1959	624	1974-92	19	Dunn, 1996
Calcasieu	4403	2404	546	1978-93	16	Dunn, 1996
Mississippi	2967000	1507298	508	1980-96	17	Goolsby et al., 1999
Red-Ouachita	241647	60497	250	1980-96	17	Goolsby et al., 1999
Texas Gulf Coast						
San Antonio	10155	3873	381	1974-93	20	Dunn, 1996
Guadalupe	13463	3492	259	1973-93	21	Dunn, 1996
Lavaca	2116	512	242	1974-93	20	Dunn, 1996
Trinity	44512	10068	226	1974-93	20	Dunn, 1996
Sabine	24162	5369	222	1974-93	20	Dunn, 1996
Neches	20593	4462	217	1974-93	20	Dunn, 1996
Brazos	116568	15147	130	1974-92	20	Dunn, 1996
Mission	1787	209	117	1974-93	20	Dunn, 1996
Colorado	109402	3945	36	1974-93	20	Dunn, 1996
Nueces	39956	1234	31	1974-93	20	Dunn, 1996
Rio Grande	456702	1315	3	1974-93	20	Dunn, 1996
South Atlantic Coast						
Columbia	670292	135800	203	1996-00	5	Kelly et al., 2001

***Table 1**. Summary of data on total nitrogen loads and yields of 60 rivers draining to Atlantic, Gulf, and Pacific Coasts. Data are arranged by decreasing total nitrogen yield within each of eight coastal zones.*

[2]The total amount of nitrogen discharged by the river /[3]The load divided by the basin drainage area.

The nitrogen loads in Table 1 represent the annual average of total nitrogen (dissolved and particulate, organic and inorganic) discharged from each river during the period summarized. The load of nitrogen flowing into an estuary along with its estuarine susceptibility (discussed earlier in this section) is perhaps the key factor affecting its eutrophication status.

In general, as the level of nitrogen in an estuary increases, so do the symptoms of eutrophication. Since large river basins drain larger areas, they usually discharge larger amounts of water and transport larger loads. This makes meaningful comparisons of the nitrogen loads of rivers impossible. However, the total nitrogen yield normalizes the load to the area of the basin making it possible to compare the relative nitrogen inputs of large and small basins. The yields can identify basins that contribute abnormally large amounts of nitrogen for its drainage area. Thus, nitrogen yields may help identify basins with excessive inputs from point and/or non-point sources.

Figure 4 graphs the nitrogen yields of the 60 rivers in Table 1. One-half of the rivers have yields of more than 388 $kg/km^2/yr$, and one-fourth of them have yields of more than 620 $kg/km^2/yr$. Rivers with the highest total nitrogen yields are in three coastal zones: the Northeast Atlantic (Charles, Blackstone), the Mid-Atlantic (Schuylkill, Susquehanna, Potomac), and the Louisiana-Gulf (Amite, Tangipahoa). The lowest nitrogen yields are in rivers draining to the South Atlantic, Gulf of Mexico, and Northwest Pacific coasts.

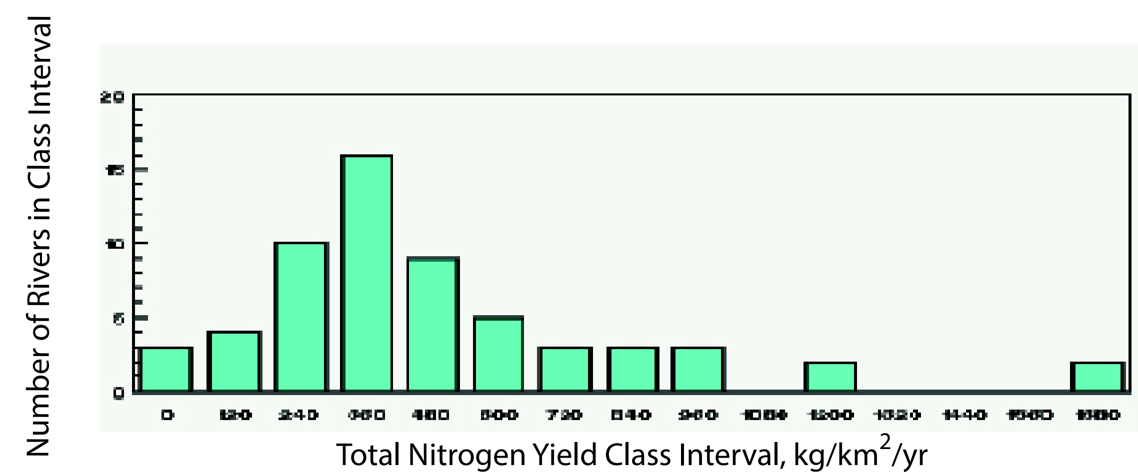


***Figure 4**. Histogram of total nitrogen yields in 60 rivers discharging to eight coastal zones of the United States as detailed in Table 1.*

The high nitrogen yield areas generally overlay the areas with high nitrogen inputs (see Table 1). An exception to this is the MRB where high nitrogen yields in the middle and upper MRB (more than 1690 $kg/km^2/yr$; Goolsby et al. 1999) are 'diluted' by large areas in the western parts of the basin where semi-arid conditions and low nitrogen inputs produce very low yields.

Generally, agricultural sources typically contribute more than one-third of the nitrogen load in most regions of the country (Alexander et al 2001). Atmospheric deposition contributes the largest amount of the nitrogen load in about half the river basins in the Northeast Atlantic coastal zone. Elsewhere, atmospheric deposition and municipal point sources contribute nearly equal amounts of nitrogen (Alexander et al. 2001).

Influencing Factors

External loads of organic matter can come from both terrestrial sources within the watershed (such as municipal waste discharges) and from decomposing wetlands. In coastal ecosystems, external nutrients can come from both the watershed and from tidal exchange with the ocean. Short- and long-term climate fluctuation can also be an important factor (Scavia et al. 2002). Alterations in precipitation patterns will modify the amount of freshwater flow, and thus, the nutrient and organic matter load reaching coastal waters.

While external loads of organic matter may influence eutrophication in some coastal ecosystems, the most important direct human cause of coastal eutrophication is the over-supply of nutrients, particularly nitrogen (NRC 2000). Estuaries have always received nutrients from natural sources from their watersheds and from the ocean; however, in recent decades population growth and related activities, such as wastewater treatment, urban runoff, agricultural runoff, natural habitat destruction, increases in impervious surfaces, and burning of fossil fuels have increased nutrient input many times over natural levels. Nevertheless, the scale and intensity of the impacts varies widely among estuaries, even among those with the same nutrient load. Varying intensities of impacts are most often attributed to differences in estuarine susceptibility. For example, variations in freshwater inflow and temperature will not only alter the flushing and stratification characteristics of an estuary, but change its susceptibility to eutrophication.

Estuarine Susceptibility

The response of an estuary to changes in nutrient or organic matter loads and symptoms of eutrophication depends on the physical characteristics of the estuary. These include the estuary volume and depth, the amount of freshwater flowing in from rivers relative to its volume, and tidal exchange with the ocean that flushes material out and brings new material in. In general, if water, nutrients, and organic matter are flushed quickly through the estuary, there is not sufficient time for problems to develop, and the estuary is not particularly susceptible. If flushing is slow (long residence time), there is time for nutrients to stimulate algal growth and for organic matter to accumulate, thereby making these estuaries more susceptible to eutrophication.

Another critical factor is whether waters within the estuary are thoroughly mixed or vertically stratified. Estuaries with physical processes that create warmer, less saline water overlaying colder, saltier water have two characteristics that enhance the symptoms of eutrophication. First, the layering keeps phytoplankton closer to surface irradiances, encouraging higher production and larger algal blooms, and second, it isolates bottom waters from the atmosphere – the source of oxygen – enhancing oxygen depletion.

This susceptibility can change seasonally and over the long-term, because key features such as freshwater load, surface temperature, and exchange with the ocean, are subject to weather patterns and changes in climate. Historical records show that precipitation in the United States has become more extreme (i.e., shorter in duration with higher intensity) over the past decades.

The ability to classify estuaries according to their susceptibility is a key factor in assessing its ability to assimilate nutrient and organic matter loads. There have been some attempts to classify estuaries in this way (see Appendix A in Bricker et al. 1999 for example), but no robust scheme has been developed to date. Based on analysis of existing data and expert evaluations of general characteristics of susceptibility to nutrients retention (Bricker et al. 1999), most estuaries tending toward increased eutrophication also retain moderate to high levels of nutrients and are over-enriched. Estuaries with low susceptibility to nutrient retention are not as enriched, have low inputs of nutrients, and low overall levels of eutrophic conditions. Of the 44 estuaries identified as exhibiting high-level eutrophication, 36 had moderate to high levels of nutrient inputs and moderate to high susceptibility to nutrient retention. In contrast, the common trait among the 21 estuaries exhibiting low overall eutrophication was less susceptibility to retaining nutrient inputs. Most of these estuaries are located in the South Atlantic region.

Not all estuaries surveyed in the NOAA estuarine eutrophication assessment followed these generalizations. For example, of the six estuaries with high eutrophic conditions and relatively low levels of human influence, five are in the North Atlantic where the susceptibility and nutrient inputs are relatively low. The symptom of eutrophication in these estuaries was toxic algal blooms, but these blooms generally originate in the ocean and drift into the estuary and are not directly responding to the nutrients in the estuary (CENR 2000b).

Consequences of Coastal Eutrophication

There is a wide range of potential impacts attributable to hypoxia and other symptoms of eutrophication (i.e., those previously described in Box 1). While some impacts, such as effects on trophic structure and integrity, are difficult to assess, many lead to more direct impairments of human use. For example, low dissolved oxygen, nuisance/toxic algal blooms, and losses of SAV directly and negatively impact estuarine resources.

Environmental Consequences

Impacts to Fish and other Organisms

Low dissolved oxygen, a direct effect of nutrient over-enrichment, is one of the most important stressors of estuarine and coastal fish populations. Hypoxia can have a variety of impacts, including reduced growth rates, increased susceptibility to predation, disruption of spawning and recruitment, and in extreme cases, mortality (Breitburg 2002). Hypoxia can also cause a reduction in suitable habitat, thus altering migration and distribution patterns and fish behaviors. Overall, such changes further lead to disruption of fisheries food webs due to changes in the relative importance of organisms and pathways of carbon flow, and thereby, to large reductions in the abundance, diversity, and harvest of fishes within affected waters (Breitburg 2002). In addition, the negative effects of hypoxia on fishes, habitat, and food webs, potentially make both fish populations and entire coastal ecosystems more susceptible to additional human and natural stressors.

Often in parallel with long-term increases in nutrient inputs are changes in nutrient ratios, as exemplified within the MRB (Rabalais et al. 1996). These changes can induce shifts in algal and benthic community structure, alter energy flows within an ecosystem, and favor opportunistic species with shorter life cycles. This results in an overall reduction in biodiversity. Another important consequence of these increases in nutrient loads and changes in nutrient ratios is that algal species that affect human health, previously absent or only present in very small numbers, are now prevalent. For example, the increased incidence of the toxic algae *Nitzschia pungen*s has been associated with amnesiac shellfish poisoning (Rabalais et al. 1996). Human health risks increase when blooms produce toxins that accumulate in fish and shellfish. Further, they may cause problems directly if airborne toxins from a bloom are inhaled (Anderson et al. 2000).

Loss of Habitat

Hypoxia and anoxia cause loss of habitat for bottom-dwelling organisms, with such loss exacerbated by other nutrient-related problems. Submerged aquatic vegetation, such as *Zostera marina* and *Potamogeton perfoliatus*, are thought to play a vital role in the ecology of nearshore environments (water one to two meters deep). These plants stabilize variable inputs of nutrients and sediment, in addition to being invaluable nursery areas for fish. SAV thrive only in relatively pristine water bodies, however. Die-offs and absence of SAV are associated with high turbidity and chlorophyll *a* concentrations caused by increased nutrient supply and thereby generally indicate a eutrophic condition (Orth and Moore 1984, Stevenson et al. 1993, Boynton et al. 1996). Additionally, high nutrient concentrations and resulting imbalances in nutrient supply ratios can lead to die-offs of SAV (Burkholder et al. 1992).

Figure 5. *Macroalgae bloom smothers the surrounding submerged aquatic vegetation (SAV) in Florida Bay. (Photo courtesy of Brian LaPointe, Harbor Branch Oceanographic Institute)*

In some estuaries, increased algal productivity caused by increased nutrient loads stimulates overgrowth of epiphytes on SAV leaf surfaces. This also often leads to die-offs or loss of diversity within SAV beds (Twilley et al. 1985, Dennison et al. 1992). Excessive growth of macroalgae (*Ulva sp.* or *Enteromorpha sp.)* smothers the surrounding SAV (Figure 5) and may also cause SAV die-off (Dennison et al. 1992).

Biochemical Impacts

Both hypoxia and (especially) anoxia can have impacts on biogeochemical processes, with consequent impacts on living resources. The most severe impacts are under anoxic conditions; they are manifest to a lesser degree under hypoxic conditions. Under anoxic conditions, ferric iron, which binds phosphate strongly, is reduced to ferrous iron, which does not bind phosphate. Phosphate also stimulates algal growth, so accelerating the release of phosphate from bottom sediments into the water column can further exacerbate eutrophication problems. In addition, reduction of sulfate to sulfide occurs in sediments under anoxic conditions, releasing hydrogen sulfide from the sediments. In the water, relatively small concentrations can be toxic to most marine life.

Anoxia also prevents the nitrification side of the coupled nitrification/denitrification cycle. Denitrification then shuts down due to lack of input material from the nitrification process, thus eliminating one potential way nitrogen is removed from water. The result is that more nitrogen is retained in the system, which contributes to persistence of eutrophication problems.

Further, as water column oxygen declines, the aerobic/anaerobic interface in the sediments moves toward the surface. This thinner aerobic interface provides a smaller barrier to diffusion of aforementioned chemical compounds across the sediment-water interface.

Socioeconomic Consequences

There are tangible and direct economic benefits of estuaries. Tourism, fisheries, and other commercial activities thrive on the wealth of natural resources estuaries supply. The protected coastal waters of estuaries also support important public infrastructure, serving as harbors and ports vital for shipping, transportation, and industry. Some attempts have been made to measure certain aspects of the economic

activity that depends on America's estuaries and other coastal waters:

- Estuaries provide habitat for more than 75% of America's commercial fish catch, and for 80-90% of the recreational fish catch (NSC 1998). Estuarine-dependent fisheries are among the most valuable within regions and across the nation, worth more than $1.9 billion in 1990, excluding Alaska (NOAA 1990).
- Nationwide, commercial and recreational fishing, boating, tourism, and other coastal industries provide more than 28 million jobs (RAE 2002). Commercial shipping alone employed more than 50,000 people as of January, 1997 (NSC 1998).
- There are 25,500 recreational facilities along the U.S. coasts (NSC 1998), almost 44,000 square miles of outdoor public recreation areas (NOAA 1990). The average American spends 10 recreational days on the coast each year. In 1993 more than 180 million Americans visited ocean and bay beaches, nearly 70% of the U.S. population. Coastal recreation and tourism generate $8 to $12 billion annually (NSC 1998).
- In just one estuarine system, Massachusetts and Cape Cod Bays, commercial and recreational fishing generate about $240 million per year. In that same estuary, tourism and beach-going generate $1.5 billion per year, and shipping and marinas generate an additional $1.86 billion per year (EPA 1997).

Impairments to Resource Use

Hypoxia and other symptoms of eutrophication can impair resource use, including causing restrictions on swimming and boating, beach closures, loss of tourism because of aesthetic and public health concerns, and restrictions on consumption of fish and shellfish. Some studies have evaluated the social and economic costs of impairments to estuaries (i.e., poor water quality leading to less fish caught, decreased tourism), but it is still not possible to provide a comprehensive assessment of the costs of such impairments to the nation. A fundamental difficulty is that few of the potential social and economic impacts are traded in open free markets where the costs can be monitored.

Although the magnitude of the impairments to estuaries cannot currently be quantified, qualitative analysis of known or suspected impairments from eutrophication or its symptoms provides some understanding (Figure 2). For example, some type of impairment was identified in 69 of the 139 estuaries surveyed in the NOAA estuarine eutrophication assessment (Bricker et al. 1999). The most frequent impairments affect commercial fishing and shellfish harvesting; impairments have been reported for all coasts. Other frequently reported impairments are aesthetics along the Mid-Atlantic coast and tourism for the Gulf of Mexico.

In addition, many of the processes leading to negative estuarine impacts produce significant impacts in the watershed. For example, the recently released 2000 Clean Water Act 305(b) report (*Water Quality Inventory)* states that nationally, a substantial number of river miles exhibit use impairments for aquatic life, fish consumption, swimming, and drinking water supply related to high nutrient conditions.

Consequences to Coastal Communities

Negative impacts on estuarine and coastal fishery resources, swimming and boating, tourism, public health, and ecological community structure and functioning, can all have social and economic effects to coastal communities. The economy of many coastal areas is based on the natural beauty and bounty of estuaries. When those resources are imperiled so too are the livelihoods of the people who live and work there. Around half the United States population, 110 million Americans, now live in coastal areas, including along the shores of estuaries. Coastal counties are growing three times faster than counties elsewhere in the Nation.

Waterfront property is important to local economies within the United States; its value is affected by the health of the water that borders it. There is a clear correlation between economic growth and clean water. Additionally, various studies indicate that low environmental risk and high economic welfare are related. These studies also show states with poor environmental quality also have below average per capita income and higher unemployment.

The estuaries and coastal areas of the United States are important to the overall economic and social well-being of the Nation. The economic impact of HABs (Anderson et al. 2000) and hypoxia have already had a negative impact on many communities within the country. Should outbreaks and the resulting negative impacts become commonplace, there will be even further economic losses.

In 1999, NOAA completed a comprehensive assessment of the scale, scope, and characteristics of

Status and Trends

nutrient enrichment and eutrophic conditions in 139 United States estuaries, including the Mississippi/Atchafalaya River Plume, using the best available information and expert opinion from academic, state, local, and Federal scientists (Bricker et al.). While this is the most comprehensive evaluation of coastal eutrophication available, gaps in data and information exist. Approaches to filling these gaps are discussed in the Recommendations section. The following discussion focuses on the status and trends of the six symptoms of eutrophication previously outlined (Figure 2; Box 1).

Status

The first response of an estuarine ecosystem to increased nutrient loads is often an overgrowth of algae, which may be indicated by high levels of chlorophyll *a*, epiphytes, or macroalgae. Strong expression of these primary symptoms indicates the estuary is likely in the first stages of eutrophication.

Of the 139 estuaries in the study, high levels of chlorophyll *a* occurred in 39; high levels of macroalgae, in 24, and high levels of epiphytes in 11. Overall, at least one of these symptoms was observed at high levels in 58 estuaries, indicating 40 percent of the Nation's estuaries may be showing the first stages of eutrophication. On a regional basis, epiphyte problems occur mostly in Gulf of Mexico estuaries, while higher levels of chlorophyll *a* and macroalgae are observed in estuaries of all regions (Figure 6). In some cases, high levels of chlorophyll *a* may be natural.

While high levels of these primary symptoms are strong indicators of eutrophication, secondary symptoms (low dissolved oxygen concentrations, loss of SAV, and nuisance and toxic blooms) indicate more serious problems, even at moderate levels. Note that while there is a causative link between nutrients and these symptoms, there are many other factors, both natural and human, which may contribute to the secondary symptoms.

Depleted oxygen was moderate or high in 42 estuaries, loss of SAV was moderate or high in 27 estuaries, and nuisance or toxic blooms were moderate or high in 51 estuaries. Overall, 82 of the 139 estuaries had moderate or high levels for at least one of these secondary symptoms. Thus, eutrophication is well-developed and potentially causing serious problems in over half of the Nation's estuaries.

These secondary symptoms vary regionally, with the exception of nuisance and toxic blooms that are observed along all coasts. A recent national assessment of HABs in United States waters (CENR 2000b) provides a thorough analysis of the regional and national status and trends, causes and consequences, and means to reduce, mitigate, and control these blooms. Losses of SAV are mostly limited to the Gulf and Mid-Atlantic regions, while low dissolved oxygen problems are observed mostly in the Gulf and Mid- and South Atlantic regions.

Low dissolved oxygen, an indicator of some of the most severely eutrophic conditions, represents a combination of information about biologically stressful oxygen concentrations of hypoxia and anoxia. The indicator takes into account the duration, frequency, and spatial coverage of low oxygen concentrations. Some estuaries exhibit low dissolved oxygen levels in the absence of human inputs. For instance, the Chesapeake Bay is known to have had anoxic areas before human settlement (Cooper and Brush 1991); however, human activities have lead to increases in the spatial extent and duration of anoxia in this system. Such natural, pre-existing conditions and variations have been taken into

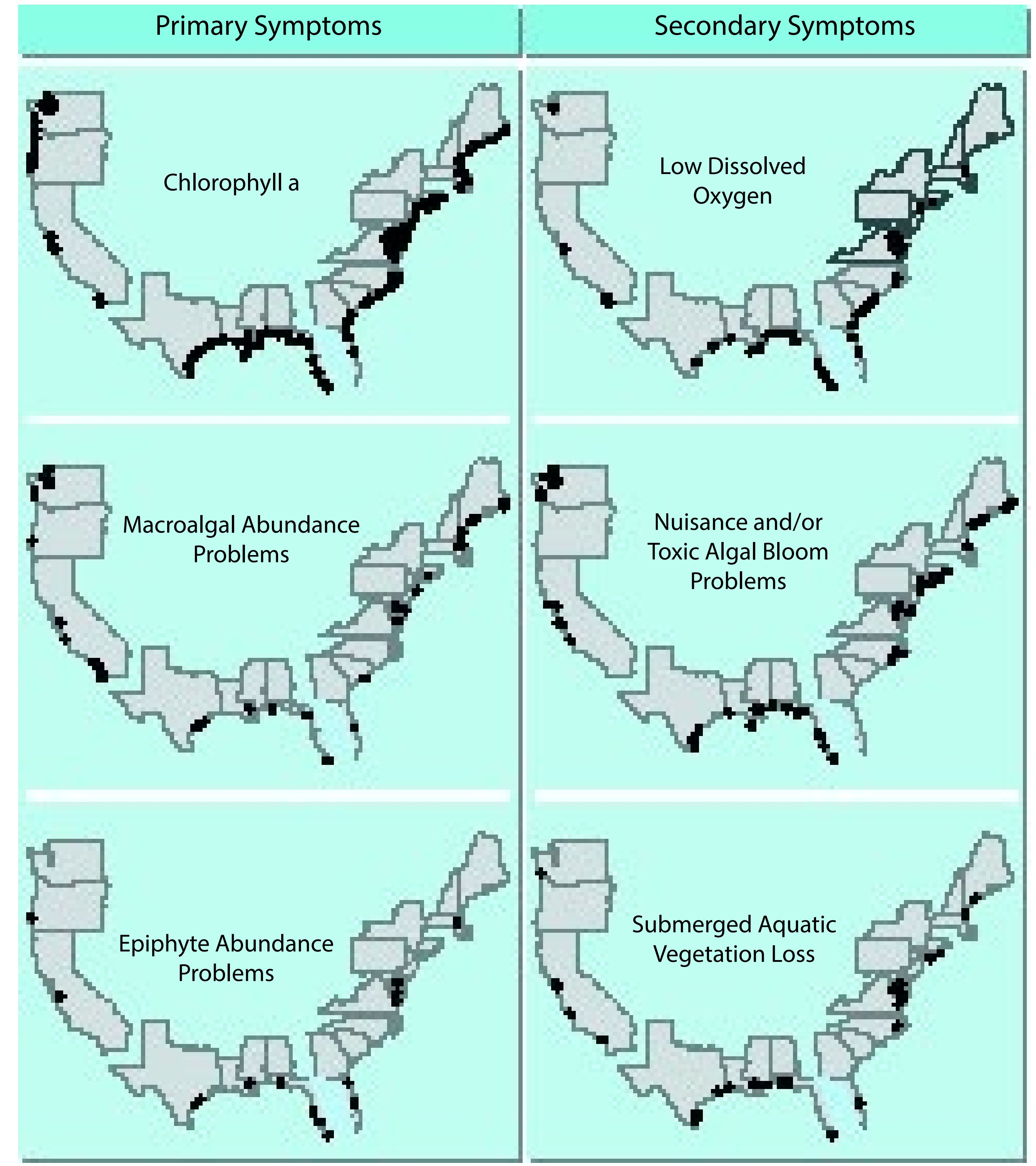
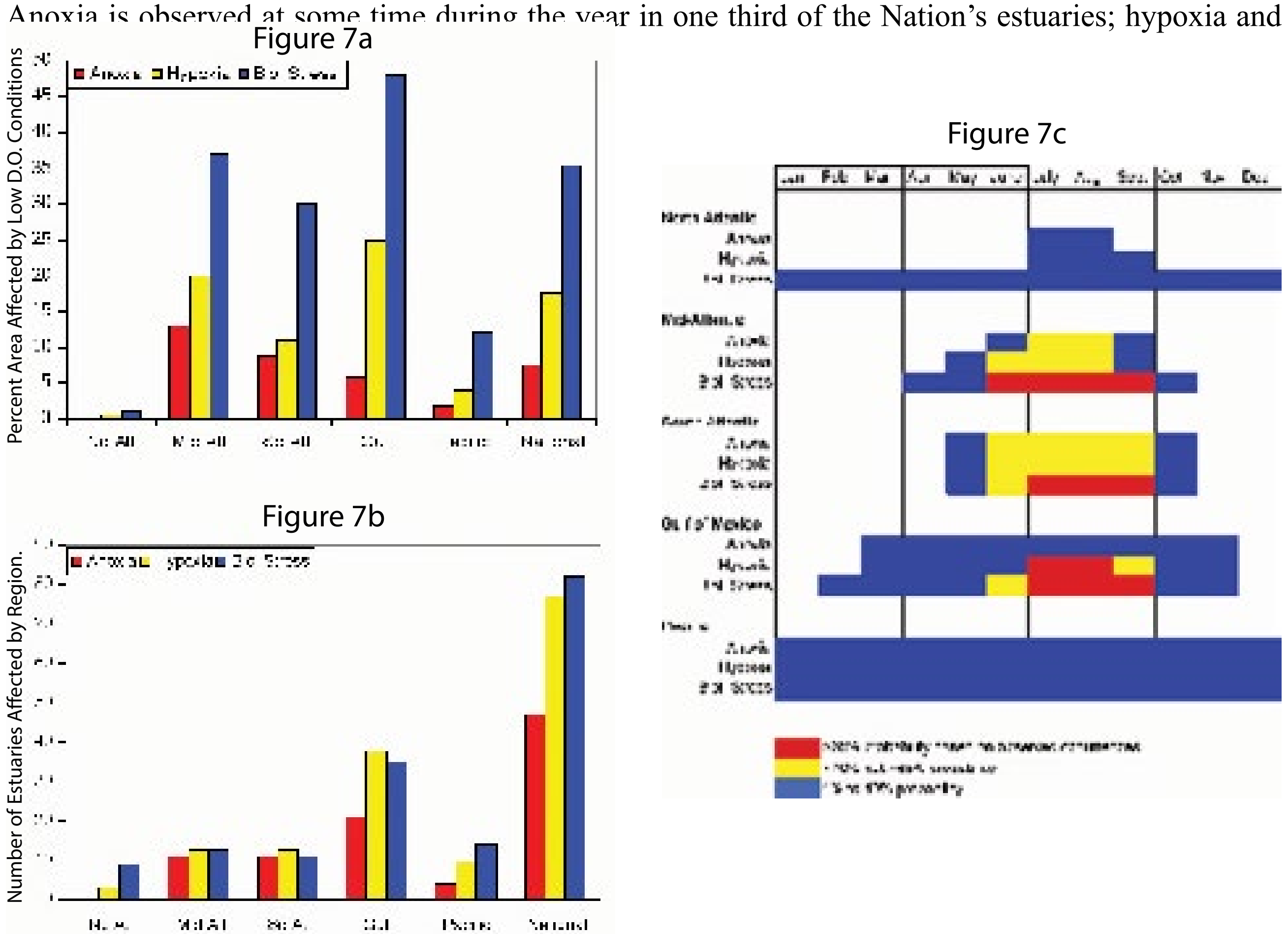


Figure 6. *Expression of Eutrophic Symptoms. The following maps depict estuaries with moderate to high levels of expression of the symptoms listed in Box1, indicating areas of possible concern. These symptoms are not necessarily related in whole to human-related nutrient inputs; natural causes and other human disturbances may also play a role to varying degrees in the expression of symptoms. (Adapted from Bricker et al. 1999)*

account in preparing the assessment. Results reported here represent dissolved oxygen conditions that are attributable to human activities.

By region and nationally, Figure 7 summarizes the extent of anoxia, hypoxia, and biologically stressful levels in surveyed estuaries. The more extreme conditions occur primarily in the summer months, though biologically stressful concentrations may occur at any time of year in estuaries of the North Atlantic and Pacific region

Anoxia is observed at some time during the year in one third of the Nation's estuaries; hypoxia and



Figures 7a-c. *The spatial area (a), the number of estuaries (b), and probable months of occurrence (c) of anoxia (0 mg/L dissolved oxygen [DO]), hypoxia (> 0 but ≤ 2 mg/L DO) and biologically stressful concentrations of dissolved oxygen (>2 but ≤ 5 mg/L DO) in United States estuaries. Figures are not meant to show cross-regional differences, but rather to highlight qualitative intra-regional differences (e.g., There are no reported incidences of anoxia within the Northern Atlantic Region). (Adapted from Bricker et al. 1999).*

biologically stressful dissolved oxygen concentrations, in more than half. The Gulf of Mexico has the greatest number and area of impacted estuaries, with biologically stressful dissolved oxygen conditions in nearly 50 percent of the region. The Mid- and South Atlantic regions also have large areas impacted by low oxygen, 30 to 40 percent of the area in both regions. The North Atlantic is the only region in which anoxia does not occur (the area of impact is less than one percent for both hypoxia and biologically stressful low dissolved oxygen conditions).

Combining primary and secondary symptoms, high overall levels of eutrophic conditions (i.e., one or more symptoms at problem levels every year over a major part of the estuary), occur in 44 estuaries (Figure 8). Although focused primarily in the Gulf of Mexico and Mid-Atlantic regions, estuaries with high symptoms of eutrophication occur along all coasts. An additional 40 estuaries exhibit moderate levels of eutrophication. It should be noted that observed conditions are not necessarily related in

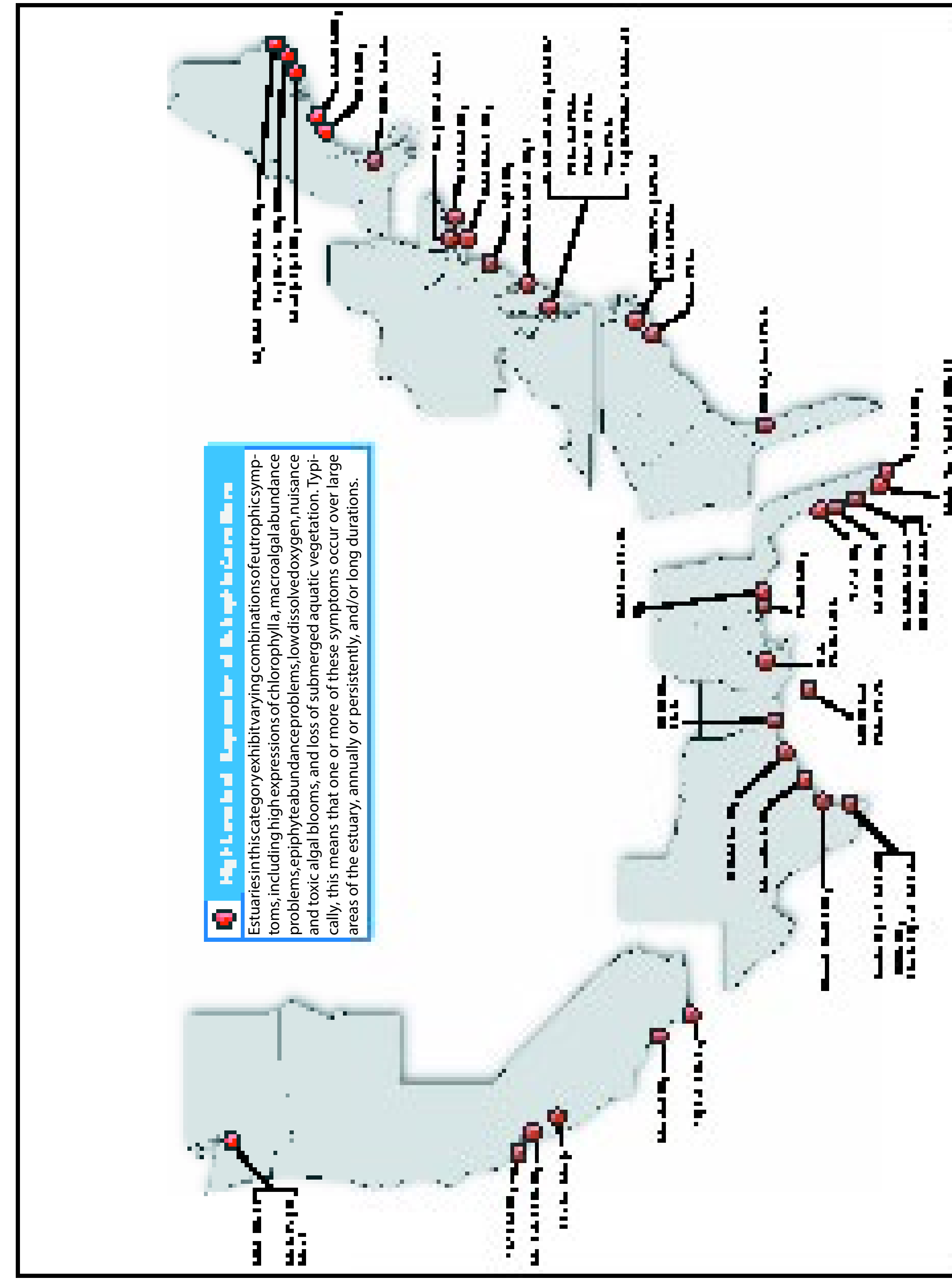


Figure 8. *Forty-four estuaries along all of the Nation's coasts were assessed as showing high expressions of eutrophic conditions, with the Mid-Atlantic and Gulf of Mexico having the highest percentages. (Note: Observed conditions are not necessarily related in whole to anthropogenic eutrophication; to various degrees natural causes and other human disturbances may also play a role.) (Adapted from Bricker et al. 1999).*

whole to anthropogenic eutrophication; to various degrees natural causes may also play a role. For instance, some estuaries in Maine are typified by natural occurrences of toxic algae, which drift in from the open ocean. Once in the estuary, however, these blooms may be sustained by human nutrient inputs.

In sum, significant problems associated with nutrient enrichment are observed in nearly two thirds of our Nation's estuaries. The remaining 38 estuaries exhibit low overall levels of eutrophic conditions. About half of these estuaries are located in the South Atlantic and Pacific regions. Further, the South Atlantic and Pacific regions contain the highest percentage of estuaries that lack sufficient information to confidently assess eutrophic conditions

Trends

Data on the assessment of trends are less certain than those for status, and for 51 estuaries, not even sufficient to draw conclusions. With the exception of dissolved oxygen concentrations, a cursory review of peer-reviewed literature suggests that between 1970 and 1995 a greater number of estuaries showed conditions getting worse with time rather than better (Table 2). Specifically, since 1970, conditions have worsened in 48 estuaries, improved in 14 estuaries, and showed no change in 26 estuaries. The greatest number of estuaries in which conditions worsened is found in the Gulf of Mexico and in the Mid-Atlantic regions; however, most estuaries that have improved are also within the Gulf region.

While there is no consistent trend data for all estuaries, data for some estuaries give some insight as to the breadth of problems experienced and the success of management actions implemented to control nutrient-related eutrophic problems in the Nation's coastal waters (see Box 2 for example case studies). The major problem in Long Island Sound is low dissolved oxygen, while in Laguna Madre, it is loss of seagrasses due to a brown algal bloom. Lake Pontchartrain has experienced difficulty with suspended sediments. Alternatively, the recovery of seagrass meadows in Tampa Bay by limiting nitrogen inputs shows how an estuary can recover if nutrient inputs are managed appropriately. The Delaware River is another example of a federal action that enabled the development of a regional entity (the Delaware River Basin Commission) to make decisions regarding the management of a regional resource. As a result of the Commission's actions and considerable investment in wastewater treatment plants, the anoxic "dead zone" was eliminated and anadromous fish have increased.

BOX 2 –TRENDS IN SELECTED ESTUARIES *(Adapted from EPA's 2001 National Coastal Condition Report)*

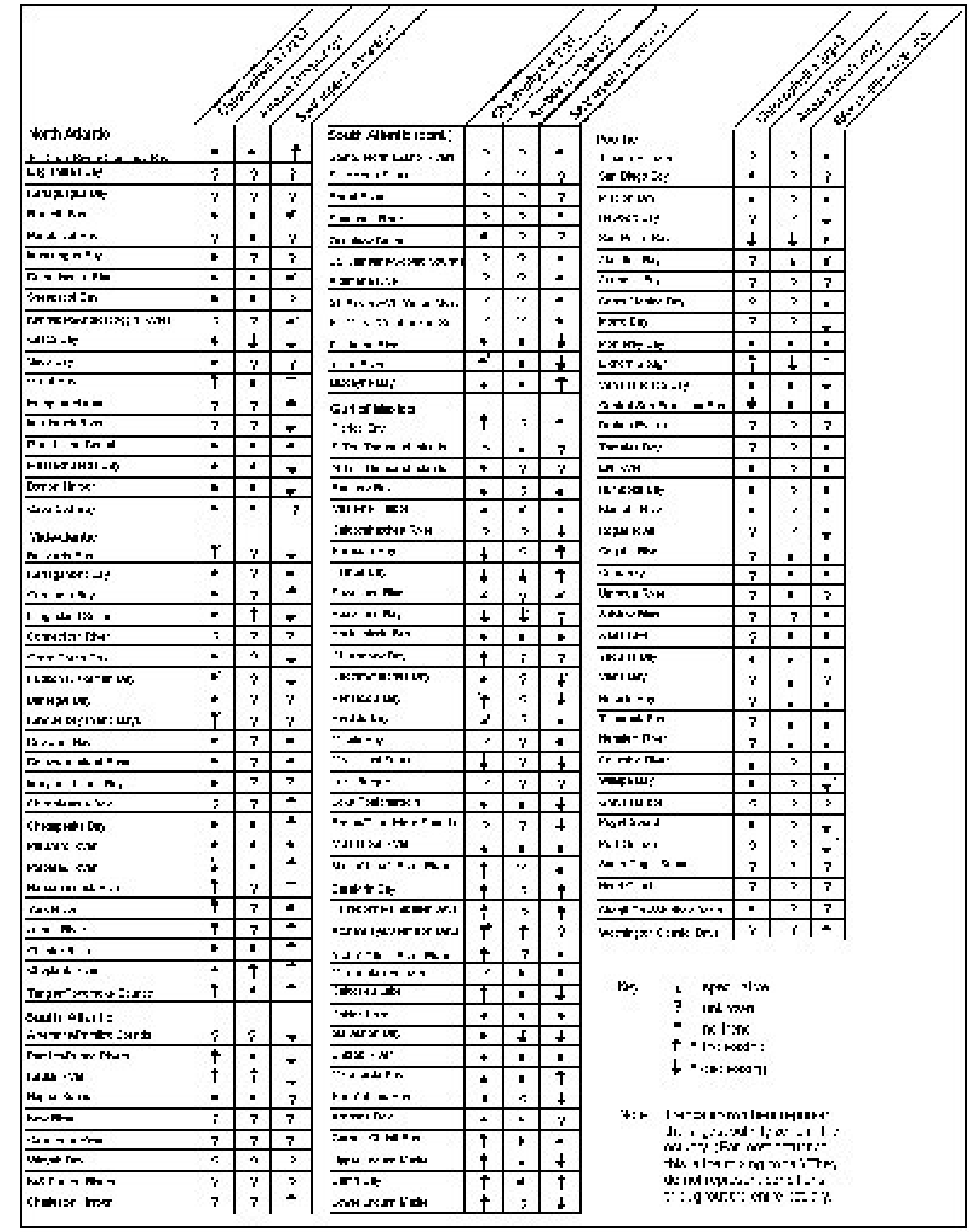
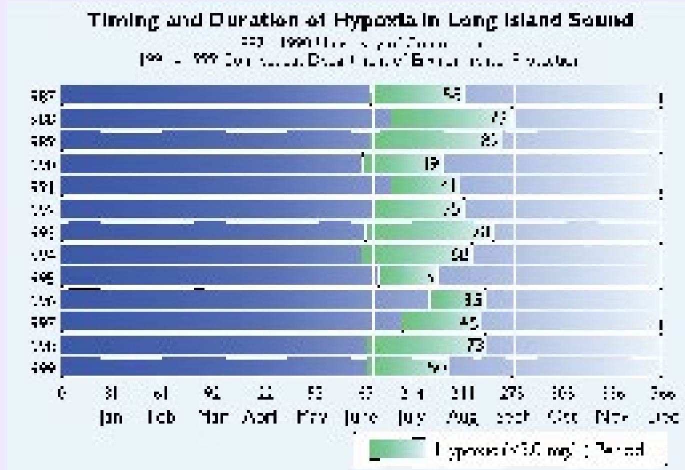


Table 2. *Trends (ca. 1970-1995) in chlorophyll a, anoxia, and Submerged Aquatic Vegetation (SAV) by estuary. (Adapted from Bricker et al. 1999).*

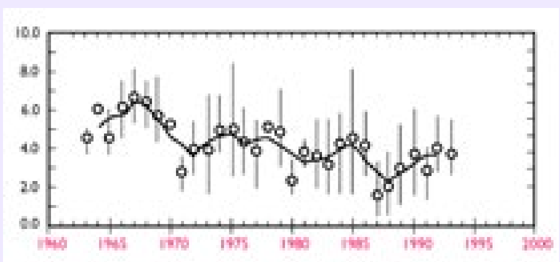
Long Island Sound, NY: Dissolved Oxygen Depletion

The Long Island Sound drainage basin is one of the most densely populated areas in the country. Approximately 8.4 million people live within the watershed, including 3.5 million in New York City. Intense resource use and human population pressures have placed a significant strain on Long Island Sound.

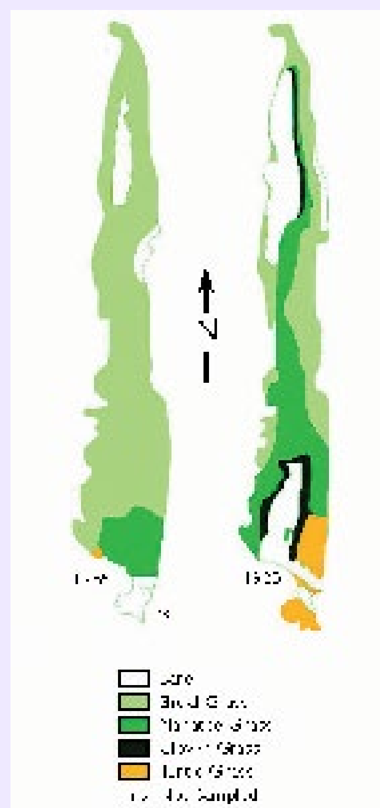


Passage of the Clean Water Act has led to measurable improvements in water quality, and many sources of pollution are now regulated. The problem of low dissolved oxygen remains a significant concern to the overall health of the Sound.

Low dissolved oxygen occurs primarily during the summer months in the central and western portions of Long Island Sound. When dissolved oxygen levels fall below 3 mg/L, the health of aquatic life tends to suffer. Water in Long Island Sound tends to be highly stratified in the late summer months and has probably always had some periods of low dissolved oxygen. Human inputs of nutrients add to the problem, resulting in more significant damage to ecologically and economically important organisms.



Average bottom water dissolved oxygen concentrations (mg/L) from 1963-1993.



Increased turbidity and changes in salinity are leading to dramatic changes in the seagrass meadows of the lower Laguna Madre (Onuf 1995).

A time series of average dissolved oxygen concentrations in Long Island Sound shows generally decreasing yearly averages form 1963 to 1993. Conditions appear to stabilize from 1973 to 1987, and to slightly recover from 1987 to 1993, but remain substantially degraded with respect to measurements made prior to 1970.

Laguna Madre, TX: Seagrass Meadow Losses

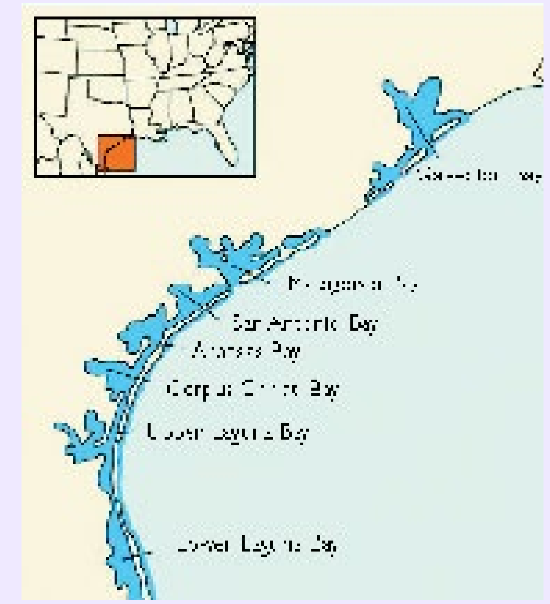
Laguna Madre is a very shallow, naturally hypersaline (saltier than seawater) coastal water body located in southern Texas near the Mexican border (see map next page). It covers over 600 square miles and averages only 2.5 feet in depth; deepest areas are only marginally over five feet. Seagrasses currently cover over 70 percent of both the upper and lower Laguna Madre. Dramatic changes are taking place in the coverage and species composition of the seagrass communities.

The upper Laguna Madre saw large increases in seagrass coverage from 1967 to 1988, but since 1988, the grasses within the seagrass meadows have been declining, particularly in the deeper areas of the lagoon. Current research suggests the declines are due to a persistent bloom of the phytoplankton *Aureoumbra lagunensis* (Texas brown tide). The bloom reduces water clarity, resulting in reduced light to the deeper seagrasses, which are then unable to survive.

BOX 2 –TRENDS IN SELECTED ESTUARIES (continued)

Seagrass coverage in the lower Laguna Madre is also declining, and species composition is changing rapidly.

Historically, shoal grass (*Halodule wrightii*) dominated these seagrass meadows. Since 1988, however, shoal grass coverage has been reduced, with only 60 percent of the original area left. Bare areas in the lagoon are increasing, and shoal grasses are being replaced by manatee grass (*Syringodium filiforme*) and turtle grass (*Thalassia testudinum*). While declines appear largely due to brown tides, sediments suspended by maintenance dredging may have also contributed to reducing the amount of light reaching seagrasses, thereby damaging the meadows.



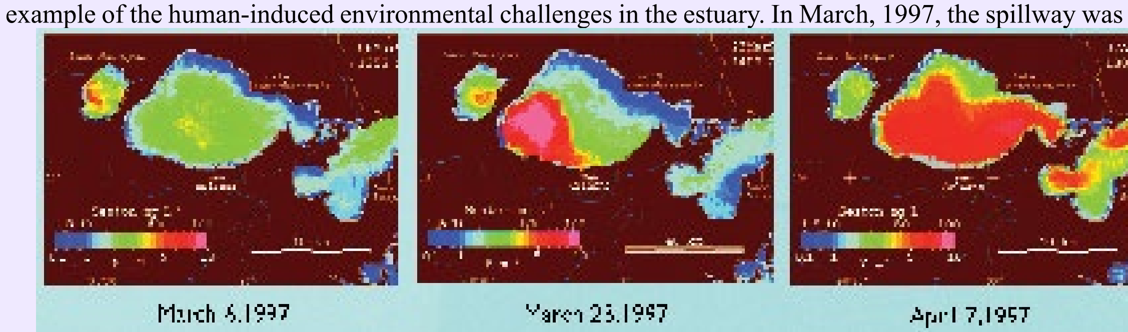
The Texas Coast.

Lake Pontchartrain, LA: A Troubled Urban Estuary

Concentrated, rapid population growth in the area between Lake Pontchartrain and the Mississippi River began nearly 300 years ago with the influx of European settlers. Today, development and urbanization in the New Orleans area is projected to continue, placing even greater stress on the Pontchartrain Basin environment.

The Basin faces many challenges, including continued loss of wetlands and estuarine habitats, water and sediment pollution, and potential impacts on the circulation patterns of water in Lake Pontchartrain from future freshwater diversions from the Mississippi River. The USGS conducts a number of long-term studies in Lake Pontchartrain to provide scientific information to help managers and planners deal with these environmental challenges.

The opening of the Bonnet Carre, which connects the Mississippi River to Lake Pontchartrain, serves as one example of the human-induced environmental challenges in the estuary. In March, 1997, the spillway was opened to divert floodwaters from the Mississippi into Lake Pontchartrain. Satellite imagery revealed an increase in suspended material in the Lake as a result of the diversion of floodwaters. The above images illustrate the increase in suspended material in the Lake as a result of the diversion of floodwaters.



Increased suspended matter in the waters of Lake Pontchartrain caused by diverting floodwaters from the Mississippi River. Red indicates suspended material. Images are derived from the Advanced Very High Resolution Radiometer instrument onboard NOAA polar-orbiting satellites.

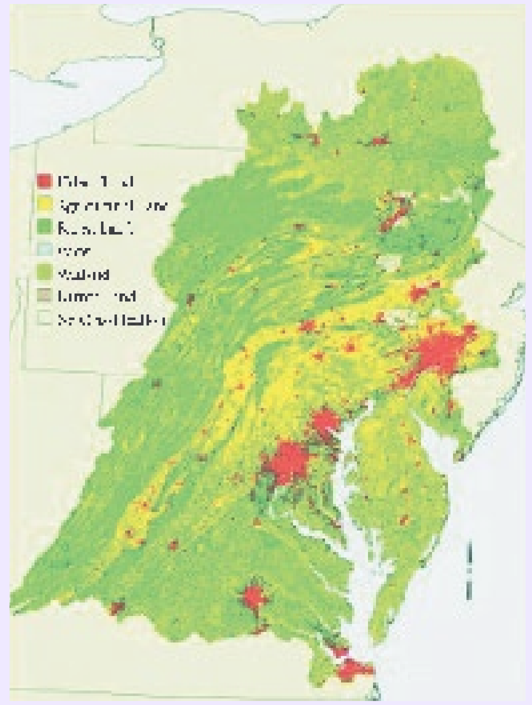
Near Coastal Mid-Atlantic Waters: Trends in Water Quality

The near coastal waters of the Mid-Atlantic are significantly affected by discharges from three major coastal systems – the Hudson River, the Delaware River, and the Chesapeake Bay. The Delmarva Peninsula lies between two of these systems; therefore, it is a major zone of influence on the near coastal water quality conditions of the Mid-Atlantic.

As in most coastal areas, a wide range of point and non-point sources contribute nutrient enrichment to coastal waters. Changes in these waters are likely related to activities in the watersheds that drain into this area. Population growth, development, and changes in land-use patterns (see figure) can all have consequences on the condition of coastal waters.

Box 2 –TRENDS IN SELECTED ESTUARIES (continued)

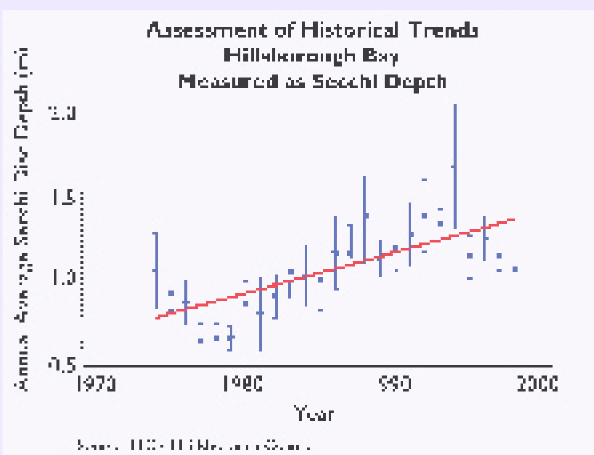
An 18-year study of the Mid-Atlantic, near-shore coastal waters (to be summarized in a forthcoming report from the EPA) show that although phosphorus levels declined in the area, the levels of dissolved inorganic nitrogen (DIN) increased significantly; in the range of 7 to 35 percent per year. Over the ten-year period, from 1982 to 1992, DIN increased significantly in the Mid-Atlantic Bight overall. This implies that biological productivity in the area may have been affected and, perhaps, lead to eutrophic conditions. The increasing DIN concentrations in the Mid-Atlantic Bight are cause for some concern, because the situation may eventually threaten both the economic and aesthetic values of the region.

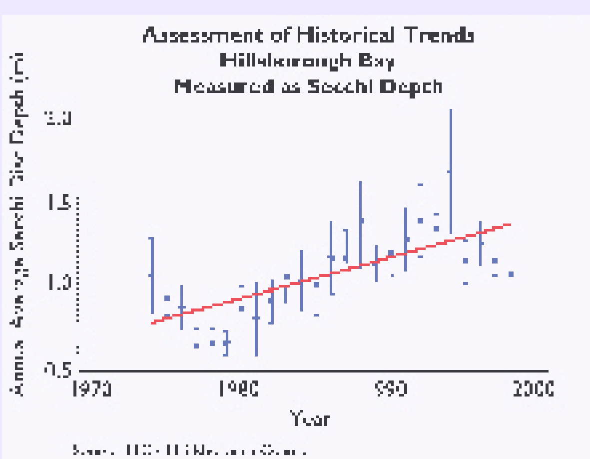


Land cover of the Mid-Atlantic region (EPA).

Tampa Bay, FL: Habitat Improves with Seagrass Recovery

In the late 1960s and early 1970s, the ecological condition of Tampa Bay declined rapidly. Polluted wastewaters, dredging and filling of estuarine and wetland habitat, and rapid development of the shoreline posed serious threats to the future of the Bay. The Tampa Bay Estuary Program estimates that more than 40 percent of the seagrass meadow acreage was lost from 1950 to 1984. A centerpiece of Florida's Gulf Coast, Tampa Bay is home to more than two million residents, receives eight million visitors each year, and contributes almost $5 billion annually to the area's economy (Liner et al. 1994).





Average annual concentrations of chlorophyll a in Hillsborough Bay, a section of Tampa Bay, dropped continuously as wastewater management plans were implemented.

Initiatives to improve wastewater management and treatment led to drastic improvements in water quality, and eventually, in bay habitat. Beginning in 1984, the frequency and duration of phytoplankton blooms declined, water clarity and oxygen levels began to improve, and seagrass cover increased.

Improvements in water quality can be seen in long-term trends in chlorophyll *a* (top graph). Reductions in chlorophyll *a* also correspond to increases in water clarity, presented here as Secchi depth (bottom graph). Historical trends also show a marked recovery in seagrass meadows. Surveys record over 5,000 acres of recovered seagrass meadow in Tampa Bay since 1984, and although the rate of expansion has decreased in some areas in the last few years, bay-wide expansion is approximately 350 acres per year.

At national scales, management strategies will primarily concentrate on the management and

Mitigation and Control

control of nutrient inputs; however, it should be noted that at local spatial scales, management strategies may also need to consider control of carbon inputs (both particulate and dissolved) if hypoxia and anoxia are to be reduced. Methods for reducing nutrient inputs specifically to water bodies fall into four categories:

1) Reducing urban and suburban sources
2) Reducing agricultural sources
3) Reducing atmospheric loads
4) Using wetlands and buffers as nutrient interceptors

This section describes these methods and provides information (where available) on the costs of implementation. Descriptions of relevant Federal and State laws can be found in Appendix A.

Reducing Urban and Suburban Sources

Nutrient loads from urban and suburban sources are discharged from point and non-point sources. Examples of these sources include municipal and industrial treatment plants, storm sewer systems, CSOs, separate sanitary sewer overflows (SSOs), construction activities, OWTSs, lawn and landscape care, and wildlife and pet waste. Stream channel and shoreline erosion may also result in nutrient discharge (primarily phosphorus) into water bodies.

Municipal and Industrial Treatment Plants

On average, secondary treatment does not effectively remove nutrients. The nitrogen content of the effluent from most secondary sewage plants is substantial (NRC 1993b). Advanced treatment is needed to significantly remove nutrients. Advanced treatment technologies include a wide range of physical, chemical, and biological methods, with nutrient removal rates of 90 percent or greater depending on the specific technology. Systems involving land application and reuse of effluent can reduce these levels even further.

A high level of engineering and maintenance is generally required to achieve significant nutrient removal reductions. Conventional physical/chemical/biological treatment technologies rely on the controlled use of chemical and mechanical energy within engineered structures. These technologies have proven successful in treatment of wastewater, especially systems with controlled flow inputs. Many of these processes are, however, expensive and labor intensive. Chemical addition with primary clarification and biological nutrient removal are the primary methods of removing over 90 percent of the phosphorus from wastewater. Nitrogen is most frequently removed through nitrification/denitrification processes, while phosphorus can be removed using chemical addition and biological treatment processes. The resulting sewage sludge can be treated and land applied as biosolids, landfilled, or incinerated. The levels of phosphorus in wastewater (and the resulting treatment costs) have been significantly reduced when states or local governments have required the use of low phosphate and no-phosphate detergents.

Storm Sewers and Combined Sewer Overflows

Stormwater from landscaped areas and impervious surfaces (e.g., rooftops, parking lots, and city streets) can result in nitrogen loads to local waterways during rainstorms. Nitrogen from CSOs can be removed using source reduction or treatment. Source reduction through education is one of the most effective means to reduce nutrient inputs. Street sweeping via modern street sweepers also can be effective in reducing phosphorus loads, since matter containing phosphorus is disposed of in a landfill instead of washing into a storm sewer. Structural practices, such as bioretention and constructed wetlands, reduce both nitrogen and phosphorus discharges into water bodies. Runoff volumes and peak flows can be controlled through the use of retention or holding ponds, reducing stream channel bank cutting and incision that can cause increases in the detachment and mobilization of soils containing phosphorus. Instead of impermeable asphalt or cement, parking lots and other large paved areas could be constructed using permeable membranes. These allow water to percolate through them into the ground instead of draining into storm sewers. This has been done in California and should be investigated as a means to decrease runoff and channeling.

Structural practices typically rely on infiltration, filtration, detention, and retention to remove or trap particles that may contain nutrients and to keep them in the soil rather than releasing them into the water. Chemical and biological activity within soils can reduce phosphorus and nitrogen discharges to surface waters or groundwater. Vegetative uptake also plays a role in the reduction of nutrient loads. Plants take up these nutrients through direct contact of their roots and the nutrients in the soil. Infiltration processes can be used to detain or retain runoff in filtration medium and porous soils. Soil engineering and bioretention are common infiltration practices used to reduce nutrient discharges. Filtration practices include grassed swales and filter strips that slow runoff velocity and allow pollutants to settle. Removal efficiencies for structural practices vary widely.

Combined CSO and SSO discharges can be significant sources of nutrients to estuaries. Separation of domestic wastewater systems from stormwater flows is the most effective method to reduce untreated discharges, but the cost is often prohibitive. A somewhat less expensive option is to increase the in-line and off-line water storage capacities of the combined sewers, so storm overflows become less common. This stored wastewater can then be treated through the municipal treatment plant when the plant can adequately handle it. Temporary holding basins and vaults are the most common methods used to divert flows and store them for later treatment. Low Impact Development is an emerging technology used to reduce the frequency and volume of CSO outfalls within a catchment or watershed. Detention or infiltration practices are the primary practices used to prevent site-level runoff from entering the combined sewer system.

CSO effluent can be treated with a variety of technologies, including artificial or constructed wetlands (NRC 1993a). The reduction of nutrient discharges from SSOs necessitates identification and repair or enlargement of sanitary systems that are leaking or are inadequate to handle the discharge volume.

Onsite Wastewater Treatment Systems/Septic Systems

Onsite wastewater treatment systems can be a significant source of nutrients to the receiving environment, especially nitrogen, because they are used where there are no municipal sewer systems and treatment. These are typically a septic tank and filter bed on a residential property. Numerous alternative system designs are available, providing varying degrees of effectiveness at removing nitrogen and phosphorus.

A number of OWTSs use biological treatment to nitrify and denitrify domestic wastewater. These systems include aerobic/anaerobic treatment to reduce nitrogen loads. Recirculating sand filters, combined with anaerobic upflow filters, can remove 70-80 percent of total nitrogen loads. Sequencing batch reactors can remove 50-80 percent of the nitrogen.

Other systems can be used to remove phosphorus. These systems, when used with low or no phosphate detergents, can reduce total phosphorus to 1 to 2 mg/L with proper maintenance (EPA 2002). They include aerobic and anaerobic biological treatment systems. Drip irrigation can reduce these levels even further.

But existing and new systems should be managed collectively to achieve the desired performance necessary to protect or restore receiving waters. Cumulative loads should be considered when developing strategies to replace existing systems or site new systems in areas where OWTS are or may contribute significant nutrient loads.

Lawn and Landscape Care

Homes and residential neighborhoods are a major source of water pollution. Impervious surfaces, such as paved areas, roofs, and even lawns do not allow precipitation to percolate through the soil. Instead, most of the precipitation flows over the land (runoff) picking up pollutants as it travels to the nearest waterbody. Further, improper lawn fertilizer use can contribute to nutrient enrichment of coastal waters. Not testing the soil before fertilizer application often results in applying fertilizers in excess of agronomic rates. Improper timing of fertilizer applications and poor soil management may also result in nutrient-laden runoff.

Efficient watering techniques can reduce runoff; over watering can increase nitrogen loss 5 to 11 times. The use of slow-release fertilizers applied at the proper application levels can also reduce the discharge of phosphorus and nitrogen to surface waters. Another simple reduction strategy is to create a “backyard” conservation buffer (allowing grass to grow wild) as the roots of the long grass hold soil in place better than a manicured lawn. Also, the grass traps sediment and nutrients before they can reach the shoreline.

Wildlife and Pet Waste

Pets and wildlife can contribute to nutrient loads in urban and suburban areas. Those wastes should be collected and properly disposed of to avoid increased nutrient loads. Requirements that pet owners properly dispose of animal feces can reduce the impact of pet waste on surface water quality.

Wildlife populations should be managed to control nutrient loads. Strategies such as ‘no mow zones’ can discourage waterfowl from frequenting shorelines and reduce nutrient loads from fecal matter.

Reducing Agricultural Sources

Over the past half-century, advances in crop and soil sciences have led to improved management strategies and technologies that increase agricultural productivity. Chief among these advances has been nutrient management strategies to provide essential nutrients for crop growth. While dramatically increasing agricultural productivity, these advances have also had adverse environmental impacts, as manifested through increased nutrient delivery from agricultural lands to surface water and groundwater. An extensive body of literature exists about the role of nutrients in crop production and the subsequent delivery of excess nutrients (originating as fertilizers and/or animal manure) to soil and surface water or groundwater (e.g., Baker and Laflen 1982; Duxberry and Peverly 1978; Mueller et al.

1984; Sharpley et al. 1993; Smith 1998).

Tools for Agricultural Producers

In 1990, the USDA initiated large field research projects in nine Midwestern states to address pesticide and nutrient impacts on surface and groundwater quality. Several agencies within USDA cooperated in this; the Agricultural Research Service, Cooperative Extension Service, and Natural Resources Conservation Service. These projects, known as the Management Systems Evaluation Areas (MSEA), provided basic tools to agricultural producers on how they can limit pesticides and nutrients reaching surface and groundwater systems (Onstad et al. 1991). Primary among the problems addressed by the MSEA projects were resolving issues related to tile drainage and soil moisture content and evaluating the impacts of cropping and tillage practices on pesticide and nutrient delivery to surface waters.

Tile drains in parts of the Upper Midwest dramatically increased the productivity of farmland by promoting earlier and more complete drying of soil; a beneficial conditions for crop production. Tile drains are typically placed one meter below the soil surface with horizontal spacing between the tiles based on soil permeability (Baker and Johnson 1981; Davis et al. 2000). Effectively placed, drain tiles intercept up to 95 percent of percolating soil water and divert it to adjacent drainages (Zucker and Brown 1998a, 1998b). The available nutrients in the soil are commonly transported with this water, redirecting them from groundwater to surface water, potentially leading to eutrophication of surface water bodies where this water is directed (Figure 9).

Crumpton and Baker (1993) demonstrated that small constructed wetlands could be used as effective filters of tile drain discharge. Their results indicate these wetlands could use as little as one percent of the total available land and still provide acceptable nutrient filtering. Mitsch et al. (2001) further suggest that constructed wetlands and riparian buffers could act as sinks for agricultural nutrients, though success of these practices varies considerably in the spatial and temporal domains (Groffman 1994; Correll et al. 1994; Gilliam et al. 1997; Mitsch 2001).

Figure 9. A dense bloom of cyanobacteria (blue-green algae) in the Potomac River Estuary downstream of Washington, D.C. Note the farm field in the upper left. (Photo courtesy of W. Bennett, USGS.)

Raising the water table in agricultural fields also can facilitate nutrient reductions in surface water by promoting the denitrification process (Jiang et al. 1998). Fausey et al. (1995) showed subsurface drains could also be used to subirrigate crops and reduce nitrogen leaching. However, elevating the water table also increases NOx emissions from the soil (Jacinthe et al. 1999), which could have negative consequences for global climate change and variability. Recent modeling efforts (Davis et al. 2000) indicate that long-term climate and nitrogen application rates are more closely linked to nitrate losses from agricultural watersheds than are changes in drain tile depth or spacing. Modeling suggests that while management of subsurface tile drains can impact local delivery of nutrients to surface waters, the most effective long-term benefits may be achieved through improved nitrogen application rates.

Links between the crops planted and nutrient delivery to surface and groundwater systems are well documented. Investigators have shown that growing corn continuously yields higher nitrate leaching than corn-soybean rotations (Rice et al. 1995; Subler et al. 1995; Varvel et al. 1995; Albus and Knighton 1998; Kanwar et al. 1997). Reduced leaching from the corn-soybean rotation occurs, partly, because fertilizers are not applied to the soybean crop as decomposition of soybean residue leads to higher soil nitrate for the corn crop that follows, thereby decreasing inputs by roughly one-half. Soybeans also are more efficient at extracting nitrates from the soil, leaving less nitrate residue in the soil to be leached. Rotation of corn with other crops (e.g., alfalfa, wheat) produced similar results (Bundy and Andraski 1995; Kanwar et al. 1995).

A number of investigators have evaluated the effects of conservation tillage practices on nutrient leaching, including ridge-till and no-till in comparison to conventional (chisel plow) technology. Results of these investigations are often site-specific. Kanwar et al. (1997) found little or no effect of tillage practices on soil nitrate leaching. Albus and Knighton (1998) described mixed results for ridge-till and mulch tillage; the results depended on the crop type (soybeans versus corn). Clay content also appeared to influence effectiveness of tillage practices to control nutrient runoff. No-till tended to reduce nitrate leaching in clay soils (Hughes et al. 1995) except where large surface cracks from soil drying increased nitrate leaching (Blanchard et al. 1995).

On-field nutrient management practices, including the rate, timing, and application method of fertilizers, have the potential to substantially reduce nutrient delivery to surface water and groundwater (NRC 2000). Randall and Mulla (2001) showed the rate and timing of fertilizer application was far more important to nitrate leaching than tillage practices. Applying nitrate fertilizer in the fall resulted in lower corn yields and increased leaching in tile drains. McIsaac et al. (2001, 2002) suggested that applying 12 percent less fertilizer on fields could reduce the nitrate-nitrogen entering the Gulf of Mexico by 33 percent. Their results were based on crude estimates of net anthropogenic nitrogen inputs that included nitrogen harvested from crops and pastures, from fertilizers, by atmospheric nitrogen fixation, by atmospheric deposition (wet and dry), and from animal manure. The non-linear response of riverine nitrate outputs to fertilizer inputs probably reflects the diminished ability of the soil to assimilate nitrogen and the in-stream denitrification process. Of greater importance, these results suggest that with only minimal decreases in fertilizer inputs, there could be substantial decreases in nitrate input to the Gulf. Using improved soil nitrate tests can also substantially reduce fertilizer application (Magdoff et al. 1984; Bundy and Andraski 1995). Nutrient delivery from agricultural soils to surface water and groundwater decreased when fertilizers were incorporated into soil bands (Lowery et al. 1995; Baker et al. 1997).

In sum, a variety of strategies exist to decrease nutrient delivery from agricultural lands to surface

and groundwater. Management of tile drainage, construction or rehabilitation of riparian buffers and wetlands, and improved agricultural management through crop rotation, tillage, and reduced fertilizer applications offer the greatest opportunities for reducing hypoxia in coastal ecosystems.

Incentive-based Strategies

The EPA released a *Water Quality Trading Policy* in January, 2003, which supports trading as an innovative mechanism to improve or preserve water quality under a variety of circumstances. The policy recognizes that within a watershed the most effective and economical way to reduce pollution is to provide incentives to encourage action by those who can achieve reductions easily and cost-effectively. For example, it would allow one source to meet its regulatory obligations by using pollutant reductions created by another source that has lower pollution control costs. However, water quality trading cannot be used to meet technology-based regulatory standards. Trading capitalizes on economies of scale and the control-cost differential among, and between, sources. For example, it could include trades between agricultural producers with non-point source runoff and municipal wastewater treatment facilities with permitted discharges.

Many of the strategies outlined herein to reduce nutrient delivery from agricultural lands to waters and to mitigate hypoxia in coastal waters can be implemented through Farm Bill programs. The Farm Bill establishes a variety of programs and incentives to manage agricultural activities that contribute to environmental pollution. Specifically, the Federal Agricultural Improvement and Reform (FAIR) Act, otherwise known as the "1996 Farm Bill" (P.L. 104-127), established an Environmental Quality Incentives Program (EQIP), which provides technical, educational, and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns. The EQIP is administered by the USDA's Natural Resources Conservation Service (NRCS).

Working with soil and water conservation districts, states identify priority areas for focusing effort, including watersheds or other geographic regions. States can also identify significant statewide natural resource concerns (e.g., nutrient management). The EQIP is implemented through conservation plans that include structural, vegetative, and land management practices. The NRCS provides cost-share payments to implement practices, such as animal waste management facilities, terraces, filter strips, nutrient management, pest management, and grazing land management. Fifty percent of the funding available for the EQIP is targeted to natural resource concerns related to livestock production.

The most recent six-year Farm Bill, the Farm Security and Rural Investment Act of 2002 (FSRIA; P.L.107-171), sets a new milestone for conservation on agricultural lands. The Conservation Title (Title II), providing funding for conservation practices, was increased by 80 percent over previous levels. This Farm Bill also improves upon the EQIP and includes two other important programs that can reduce land-based sources of pollution, the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP). These two programs provide incentive payments to encourage farmers to convert highly erodible cropland or other environmentally sensitive acreage to vegetative cover, such as grasses, wildlife plantings, trees, filter strips, or riparian buffers. Farmers receive an annual rental payment for land taken out of production, and cost sharing is available to establish the vegetative cover practices. The CRP and CREP provide a tool to establish additional buffering capacity where nutrients are contributing to hypoxia.

In addition to the Conservation Title, a separate Forestry Title (Title VIII) was added that is also relevant to conservation practices and water quality. In sum, there are 14 conservation programs in the 2002 Farm Bill (see Appendix A for expanded descriptions) that either directly address water quality and wetlands or that relate to water quality improvements through the conservation or restoration of natural or managed lands.

Reducing Atmospheric Loads

Fortunately, because NO_x emissions are a primary contributor to ozone and smog in the lower atmosphere and to acid rain across the Nation, controlling them has received substantial study (NRC 2000). Activities that focus on meeting the ozone standard can also result in reductions in nitrogen deposition. These include transportation changes, such as reductions in growth of vehicle miles traveled through increases in public transportation, or restrictions on emissions from local point sources.

Control of both mobile and stationary sources of nitrogen involves facilitating complete combustion so that NOx emissions, released in less efficient combustion, are transformed into inert nitrogen gas. Stationary source reductions involve controlling combustion or post-combustion processes. In the first, the combustion process modifies the coal-air mixture or re-burns flue gases, reducing NOx emissions 35-72 percent. Post combustion processes involve injecting flue gas with a catalyst, which can reduce NOx emissions 35-90 percent.

Emissions from mobile sources and the transportation sector are addressed by requirements for motor vehicles, fuels, and non-road engines (e.g., aircraft, boats, trains, farm and garden equipment). Mobile source controls are implemented via base engine emissions, air-fuel ratio control, better fuel delivery, and atomization and treatment of exhaust. Engine improvements increase the engine thermal efficiency, and thus, the combustion process, and can lower NOx emissions as much as 35 percent. Control of the fuel-to-air ratio is also designed to maximize engine combustion efficiency, reducing nitrogen emissions as much as 35 percent. Treatment of exhaust involves catalytic conversion, which reduces emissions as much as 57 percent. Additionally, there are advanced technologies being developed, such as hybrid- and hydrogen-fueled cars, that provide very low or no emissions. When implemented, the Tier II rule for new cars and light trucks and the Heavy Duty Diesel truck rules will result in reductions in nitrogen deposition. At the state level, motor vehicle emissions inspections and maintenance programs are an important component of mobile source emission reductions.

Additionally, nitrogen coming from the air is a significant contributor to eutrophication. To reduce the nitrogen in the atmosphere (and therefore, what ends up in the water), there needs to be effective coordination between coastal program managers and air program specialists in monitoring, modeling, and regulation. There are Federal, state, and local tools that may aid in reducing atmospheric load. Programs that assist states and localities in providing transportation projects that reduce emissions from transportation sources, such as DOT's Congestion Mitigation and Air Quality Improvements Program, can help reduce NOx loads. Title IV, the Acid Rain Cap and Trade Program of the Clean Air Act (CAA) Amendments of 1990 (P.L. 101-549), was created to reduce the adverse effects of acid rain deposition by reducing and limiting the rates of NOx and sulfur oxide emissions from electric utilities. The implementation of this program may reduce NOx emissions from both electric utilities close to the coast, as well as those much farther inland.

The EPA's ambient air quality program established National Ambient Air Quality Standards for acceptable concentrations of specific pollutants in outdoor air. Nitrogen dioxide is one of the pollutants, and States are required to have State Implementation Plans (SIPS) describing how they will achieve the acceptable concentration in various areas if they are out of compliance. The standards themselves do not take into account the potential impacts on coastal ecosystems from nitrogen deposition; however, when the NOx SIP Call is implemented, there will be reductions in nitrogen deposition.

Using Wetlands and Buffers as Nutrient Interceptors

The previous discussions presented approaches for reducing sources of nitrogen to the environment. Another, often complementary, strategy is to enhance nitrogen sinks in the landscape. Wetlands, ponds, and riparian zones are particularly effective nitrogen traps, serving both to settle out particulate nitrogen and to convert reactive biologically available nitrogen into harmless nitrogen gas through the process of denitrification (NRC 2000; Howarth et al. 1996). Small woodland streams are also extremely effective sinks, if they are not significantly disturbed (Peterson et al. 2001).

Interest and research in using wetlands and riparian buffers to reduce nutrient and toxic loads has increased in recent years. Even a partially functioning wetland or buffer can significantly reduce nitrogen loads. Therefore, preserving the wetland or riparian forest buffer is more effective at removing non-point source pollutants than waiting until they are destroyed and then restoring them. Unfortunately, in the United States a net loss of 644,000 acres of wetlands to upland land-use occurred between 1986 and 1997 (Dahl 2000); urban development accounted for 30 percent of this loss, 26 percent to agriculture, and 21 percent to rural development.

Urbanization causes significant changes to hydrology, greatly increasing runoff volume, with ensuing erosion and sediment loading. Pollutants found within this runoff vary widely, from common organic matter to highly toxic metals (EPA 1977). Mitigation of urban runoff begins with site planning and design. The incorporation of stormwater retention sites, including the use of bioretention technology; constructed and natural wetlands, vegetated buffer areas, and low-impact development strategies, can significantly reduce runoff from the urban environment.

In addition, there are numerous other benefits of urban stream buffers, especially when they are designed to include the 100-year floodplain or other established wetlands (CWP 2000a). Such riparian buffers provide effective pollutant removal, prevent stream bank erosion, reduce or eliminate the need for expensive flood control structures, and reduce the construction of additional impervious surfaces. According to Galat and Frazier (1996), nonstructural flood control mechanisms, such as natural and restored wetlands and upland and riparian vegetation, can impound significant flood waters and stabilize erosion. Even grass or forest buffers merely 30 to 100 meters wide can provide significant benefits (Galat and Frazier 1996).

The suburban landscape significantly contributes to nutrient and sediment loads as well. According to the Center for Watershed Protection (2000b), there are an estimated 25 to 30 million acres of lawn and turf in the United States. Fertilizer application rates on these lawns are equivalent to that used for row crops. Indeed, if lawns and turf were classified as a crop, they would rank as the fifth largest crop in the United States (USDA 1992). A survey of residents around the Chesapeake Bay showed that 89 percent of the citizens owned a lawn, and about 50 percent of those applied fertilizer every year (Swann 1999). The majority of landowners did not know the phosphorus or nitrogen content of the fertilizer they apply, and only 10 to 20 percent had soil tests performed to determine if fertilizer was actually needed (CWP 2000b). In addition, a significant percentage of homeowners over-fertilize their lawns; 52 percent in the Chesapeake Bay survey, and as high as 65-70 percent in other surveys (Morris and Traxler 1996, Knox et al. 1995).

The tile drains used in agricultural lands in much of the United States (see the discussion under Reducing Agricultural Sources) are necessary to grow most row crops, but they also facilitate nitrogen leakage. Constructed and restored wetlands, riparian buffers, and other drainage modifications can reduce these nutrient loads through filtration, deposition, infiltration, absorption, and denitrification. These systems can be strategically placed along the edge of the field or adjacent to water bodies to intercept nutrient runoff before it enters lakes, streams, rivers, and estuaries. Research by Dillaha and Inamdar (1997) indicates effectiveness of vegetated filter strips for total nitrogen removal is 50-90 percent depending on length of the strip. Nitrogen removal from constructed wetlands varies widely, from 10-76 percent.

These wetland systems can also be used to treat wastewater effluent. Typically, wetlands are constructed for either surface flow over the substrate or sub-surface flow through a substrate. They require much more land than environmental technologies (e.g., retention ponds). Removal efficiencies range from 46-72 percent, consistent with the engineered technologies. The generally lower cost of these wastewater treatment wetlands, however, adds to their desirability as nitrogen control systems. Costs for these systems vary widely, depending on the width of the buffers, whether new vegetation is being established, and the extent of area and volume of runoff that will be treated. Assuming an average filter strip is 66 feet wide[4], the cost in 1990 was $85.41 per acre; the average constructed wetland project cost approximately $20,000 in 1992.

Data from a recent study by Teels and Danielson (2001) indicate smaller streams are more likely to be affected by surrounding human changes in land-use, whether by agriculture, suburban sprawl, or urbanization. Using the Index of Biotic Integrity methodology, Teels and Danielson compared smaller streams in Northern Virginia, finding that high levels of forest, wetland, and intact riparian habitat were associated with healthy streams. They concluded that the need to maintain vegetated buffers and use 'best management practices' (BMP) to protect small streams was of utmost importance in maintaining biological integrity of a watershed.

To address this issue, scientists have begun to initiate nutrient reduction programs throughout the United States. For example, as part of an overall nutrient reduction strategy for the Chesapeake Bay, researchers have established a goal of restoring 100 square kilometers of wetlands within the Bay watershed over the next ten years. On the Mississippi River, restoring water flows through the wetlands of the Mississippi River delta could play a significant role in reducing the nitrogen levels on the continental shelf, where they contribute to the Gulf's hypoxic zone. Using wetlands and riparian buffers as interceptors of nutrient-rich runoff waters has been well documented and represents a scientifically sound means of reducing the effects of agricultural, urban, and suburban development worldwide.

This section outlines recommendations and management approaches for reducing nutrient inputs

[4] The width of the strip can affect its cost, but more importantly, the width definitely has an impact on the efficiency of nutrient removal.

Recommendations

to coastal ecosystems. It also outlines the research needed to reduce uncertainties associated with documenting the status, trends, and causes and consequences of coastal eutrophication. This is followed with recommendations related to the roles of Federal agencies, especially in avoiding duplication of efforts. All proposed programs and activities in this section are subject to the availability of resources.

Watersheds and Adaptive Management

Addressing coastal nutrient problems requires understanding how activities in the watersheds and airsheds directly affect nutrient inputs to the Nation's rivers and streams. This understanding should be built into both planning and implementation. It must take into account governmental units that must be involved, the geographic scale at which the problem is addressed, and the sources of nitrogen pollution.

Further, pollutant sources vary widely, from agricultural production, including crops and animal operations, to wastewater treatment, including septic systems and municipal facilities; to airborne sources, including cars, trucks, and fossil fuel combustion (both point and non-point sources are important). National policies and programs related to agriculture, transportation, energy production, and wastewater management could have a significant effect in reducing nitrogen pollution.

Watershed Approaches

The NRC report *New Strategies for American's Watersheds* (1999), as well as other studies, recognize that watersheds are the optimal geographic units for dealing with water management and closely related resources. A watershed approach uses a hydrologically defined area to coordinate water resources management. The approach is advantageous because it allows consideration of all activities that affect the watershed health. It can also highlight relationships among land management decisions, everyday actions, and watershed health, including the coastal waters. It provides a framework to consider needs that are usually looked at individually, if not in competition with one another, such as water quantity and quality, flood control, navigation, fisheries, biodiversity, habitat preservation, and recreation. Further, planners can examine local priorities in the context of national goals and facilitate public and private actions. Thus, the watershed approach should be used to plan careful, long-term solutions to problems and provide sustainable resources.

There are many examples of large watersheds in which the runoff of excess nutrients impairs coastal waters. Notable examples include the Long Island Sound, the Chesapeake Bay, and the Gulf of Mexico. All show nutrient pollution is a watershed problem and must be addressed as such (see Box 3 for example case studies).

The Chesapeake Bay watershed stretches across six states and the District of Columbia and includes a number of smaller 'subwatersheds.' More than 64,000 square miles of land drain into the rivers that feed the Bay. When accounting for all the nutrients that enter the Bay, the two largest contributors of both nitrogen and phosphorus are agriculture and point sources. Forests are a natural source of nutrients.

The Long Island Sound watershed covers about 16,000 square miles, extending from Canada through five states. The watershed drained by the Connecticut River alone is about 11,000 square miles. Wastewater treatment facilities are the source of most of the excess nitrogen.

The approximately 5,500 square mile hypoxic zone in the Gulf of Mexico results from nitrogen draining from the 31 states in the MRB. Agricultural production is the largest source of excess nitrogen and is located in the upper portions of the basin: Minnesota, Iowa, Illinois, Indiana, and Ohio.

Strategies for reducing nutrient loads from watersheds must include significant roles for local watershed and coastal managers in addition to the important role for Federal and state governments. As is being developed for the watersheds described above and for other areas, the focus should be on reducing nitrogen inputs at their source. Specific sources, such as urban stormwater runoff and inadequate nutrient management on farms, are most effectively and best addressed by local leadership, since activities are typically site-specific. While improvements may be achieved through local action, local managers alone cannot contribute adequate resources and expertise to solve this complex problem. Often local watershed efforts may not be effective outside a larger watershed context. Thus, it is essential that local, state, and Federal governments work together, along with the private sector, universities, and local citizens/activists.

One example of a watershed strategy to address hypoxia is the 2001 *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (EPA 2001a). A task force of Federal, state, and tribal representatives developed the strategy with input from local organizations and the private sector. Meetings were held in Washington, D.C., and throughout the watershed. The actions recommended range from expanding monitoring programs, examining nutrient reduction through Army Corps of Engineers projects, and restoring wetlands, to better targeting of voluntary BMP for controlling nutrient runoff from agricultural lands. The Plan also includes sub-basin committees to coordinate implementation actions by major sub-basins and smaller watersheds.

Unlike many other pollutants, nitrogen *concentrations* are poor predictors of effects in the coastal zone. Thus, a strong scientific consensus exists that nitrogen pollution should be managed on the basis of nitrogen *loads* (NRC 2000) and use a watershed approach to estimate and control allowable nitrogen sources. One approach assumes that all coastal ecosystems respond similarly is based on cross-system analyses and models of the average response of coastal ecosystems to increased inputs (e.g., NRC 1993a, 2000; Nixon 1995). Because coastal ecosystems vary in their sensitivity to nutrient inputs (see the discussion on Estuarine Susceptibility), a more cost-effective approach may be to allow higher nitrogen loads in ecosystems that are less susceptible and restricting loads only for more sensitive systems. The conceptual design of the Total Maximum Daily Load (TMDL) provision of the Clean Water Act uses allowable loads as a basis for management. After that, actions ranging from permits under the National Pollutant Discharge Elimination Systems, to voluntary, incentive-based management measures could be implemented to reduce nitrogen loads.

Since the sources of nitrogen and coastal ecosystem sensitivity to this pollutant vary, rather than setting a national goal of nitrogen reduction per se, the *Clean Coastal Waters* report (NRC 2000) recommended a national goal of protecting ecosystems not yet damaged and restoring those that have been damaged. The NRC called for a partnership of "Federal, state, and local authorities … [working] with academia and industry to:

- Reduce the number of coastal water bodies demonstrating severe impacts of nutrient over-enrichment by at least 10 percent by 2010;

- Further reduce the number of coastal water bodies demonstrating severe impacts of nutrient

over-enrichment by at least 25 percent by 2020; and

- Ensure that no coastal areas now ranked as 'healthy' (showing no or low/infrequent nutrient-related symptoms) develop symptoms related to nutrient over-enrichment over the next 20 years."

BOX 3 – CASE STUDIES OF WATERSHED APPROACHES

Chesapeake Bay – The latest agreement, *Chesapeake 2000,* commits Bay watershed partners to "complete a public process to develop and begin to implement 'Tributary Strategies'." These strategies are detailed, local action plans (e.g., riparian forest buffer replanting, wastewater treatment upgrade, nutrient management on farms, stormwater treatment, and stream restoration). Action plans specify how and when such actions may be implemented. The goal is to reduce nutrient and sediment loads from each of the 37 sub-basins in the Bay watershed by 2010. Local governments, watershed associations, regional organizations, and other local stakeholders have participated in developing these strategies. (http://www.chesapeakebay.net/nutrl.htm)

Long Island Sound – Working since 1990 with the EPA and other agencies at all levels of government, Connecticut and New York have implemented a phased program to reduce nitrogen loads, to improve dissolved oxygen levels, and to meet water quality standards in the Sound. In 2001, the EPA approved a nitrogen TMDL consistent with *Phase III Actions for Hypoxia Management*. A two-state agreement established a goal of reducing nitrogen loads in the Sound 58 percent over a 15-year period ending in 2014. Some of the specific actions include upgrading secondary treatment facilities in New York and a Connecticut Nitrogen Credit Exchange program that allows municipalities to trade nitrogen credits. The credits save funds that would be needed for wastewater facility upgrades to control nitrogen discharges. In addition, Westchester County, New York, with six other municipalities, completed a plan for controlling polluted stormwater. The plan identified municipal ordinances, stream and wetlands management, and public education (e.g., proper lawn maintenance and pet care), as ways to control nonpoint sources of nitrogen loading.

Mississippi/Atchafalaya River Watershed – The Mississippi/Atchafalaya watershed was assessed to determine the causes of Gulf of Mexico hypoxia, as influenced by its continental-scale watershed (CENR 2000a, Rabalais et al. 2002). The authors of the assessment concluded that 90 percent of the nitrate load to the Gulf comes from non-point sources - 74 percent from agriculture alone – and that almost 60 percent of the nitrate load enters the system north of the Ohio River with the primary source of that non-point load from agricultural sources from mid-western states. They estimated that decreasing nitrogen loads 20-30 percent would increase bottom-water oxygen concentrations 15-50 percent and that the net unit costs of several reduction schemes were comparable. For example, for a 20 percent load reduction, application of Best Management Practices costs $0.80, reduced fertilizer application rates, $0.67, and construction and maintenance of wetlands, $1.00. Such analysis supports the idea of regionally targeting approaches based on local social, economic, and environmental conditions.

Tampa Bay – The Bay's 2,300 square-mile watershed encompasses five counties and five major rivers. The boundary of the airshed is difficult to determine, as it varies depending upon changes in climate patterns. Transport of some nitrogen may occur over thousands of miles. Tampa Bay is Florida's largest open-water estuary. It spans almost 400 square miles and is dominated by seagrass. Since 1982, strategies have reduced nitrogen inputs from wastewater treatment facilities by 50 percent. Yet, while recovery is occurring bay-wide, it is not occurring at the rate anticipated, so further study and adaptive management may be needed.

Federal agencies should coordinate with state and local partners to advance the goal of reducing nutrient loads and protecting coastal waters from hypoxia. These activities should :

- Facilitate accessible data, information, and expertise
- Improve monitoring capabilities
- Undertake periodic assessment of coastal water conditions
- Determine vulnerability of coastal waters to hypoxia
- Support watershed and coastal managers and local initiatives
- Focus research;
- Measure progress against annual and long term performance measures indicative of water quality and overall ecosystem health.

Adaptive Management

The complex nature of nutrient cycling and transport within watersheds and the complex physical, chemical, and biological dynamics of estuarine and coastal ecosystems, make it difficult to predict estuarine responses to actions on land. Nutrient cycling is affected by atmospheric, watershed, riverine, and marine processes. Many of those processes, such as nitrogen transformations in rivers, are not fully understood. System-wide syntheses that integrate knowledge across disciplines and through time and space are difficult, and even when these assessments are drawn from the assembly and peer review of considerable scientific information, there will always be uncertainties in the analysis. In addition, estuarine responses to management actions in the watershed may be slow, possibly requiring decades before statistically reliable new trends are detected. Therefore, it is critical that management decisions allow for re-analysis and adjustments as more information becomes available. This is an adaptive management framework, which includes a comprehensive program of monitoring, interpretation, modeling, and research.

Whole-ecosystem monitoring allows interpretation of the processes and links affecting nutrient concentrations and transport within the watershed and the development of symptoms of eutrophication. These coordinated monitoring efforts must be able to:

- Detect environmental trends to evaluate the effectiveness of management actions and to enable effective adaptation of strategies over time;

- Observe physical, chemical, and biological processes and their roles in the cause-and-effect relationships between nutrient inputs and resulting environmental quality; and

- Differentiate among trends caused by changes in climate, streamflow, nutrient and landscape management measures, and other concurrent factors.

Coordinated research efforts improve monitoring designs, support the interpretation of monitoring data, and increase the predictive power of models and other assessment tools used in the management process. For complex watershed/estuary systems, monitoring and research should be integrated using models that simulate how the system functions and how management practices can best be implemented. Such a framework would not only include monitoring programs, but also use integrated models of hydrologic and ecological systems for interpretation of system change. Such models include a set of conceptual, functional, and numerical formulations; integrate research findings; and are tied to monitoring programs designed to both provide input variables and verify model outputs. An effective modeling framework would include models that simulate:

- Transport and transformation of nutrients (i.e., nitrogen, phosphorus, and silica) from natural, urban, and agricultural landscapes to groundwater and surface waters;

- Inputs and outputs of nutrient flow throughout the landscape to improve estimates of nutrient mass balances;

- Biogeochemical cycling and water quality effects of those nutrients on tributary ecosystems

within the watershed;

- Oceanographic and climate influences on those nutrients and their impacts on estuarine productivity; and

- Impact of altered nutrient flux on estuarine productivity.

Reducing Uncertainties

The 1999 NOAA estuarine eutrophication Assessment (Bricker et al.) identified uncertainties in the state of our knowledge of the status, trends, and causes of coastal eutrophication. While there was a high level of confidence in the information on over 80 percent of estuaries rated as moderately or highly eutrophic, the confidence level was much lower for over half of the systems rated with low eutrophic conditions. Most assessments with low confidence were estuaries in the Pacific and South Atlantic regions. For 17, primarily west coast, estuaries there was not enough data to make an assessment. For 32 other systems, some of the information was rated as speculative because it was based on spatially or temporally limited observations (Bricker et al. 1999).

Clearly, the Nation needs a comprehensive program of coupled, mutually informative monitoring and research to establish the status and trends and resolve the mechanisms of coastal eutrophication and hypoxia. Observation and experimentation must be coupled interactively with the development of predictive models upon which adaptive management strategies depend (EPA 2001a). This need to link monitoring, research, modeling, and management has also been identified repeatedly by the NRC (1993a, 1993b, 1994, 1999, 2000) and other assessments (Conley 2000; EPA 1998; GAO 1999).

The following discussions contain a summary of the priority information needs in four areas of the study of coastal eutrophication:

(1) Impacted and susceptible coastal waters
(2) Watersheds draining into impacted and susceptible coastal waters
(3) Predictive modeling of the watershed-coastal system
(4) Strategies for management of impacted and susceptible coastal ecosystems

(1) Impacted and Susceptible Coastal Waters

Assessment of the Sensitivity of Coastal Ecosystems to Nutrient Pollution. Coastal environments and ecosystems may respond differently to similar nutrient loads. For example, the Chesapeake Bay receives annual nutrient loads from river runoff and local urban discharges roughly similar to those delivered to San Francisco Bay and Delaware Bay and *less* than that supplied by the Hudson River to its estuary; yet the Chesapeake is regularly and significantly more eutrophic than the other three. These are four well-studied estuaries, and the reasons for the differences in response are reasonably well understood.

The majority of coastal ecosystems have not received the same level of scientific and political focus, and the relative importance of local hydrography, water mixing, light penetration, ecosystem structure, and other factors needed to determine the response to nutrient enrichment is unknown. Also, no general tool exists for assessing their sensitivity to nutrient pollution; that is, there is no scientifically robust, quantitative, conceptual paradigm for understanding how system-specific attributes (biological, physical, chemical, geological) dampen, constrain, or enhance the responses of coastal ecosystems to nutrient enrichment (Cloern 2001).

There is a clear need for research to develop a scientifically-based paradigm, as well as a classification scheme, that will enable managers to understand how susceptible an estuary is to nutrient over-enrichment (NRC 2000). With such tools, management, monitoring, and research efforts could be put into restoring and protecting the coastal ecosystems that are likely to be most severely impacted by increasing nutrient inputs.

As a research priority, the development of these tools will require:

- Dose-response curves for a variety of coastal ecosystems to nutrient enrichment.

- Integrated physical and biological descriptors of ecosystems, using standardized approaches for estimating various parameters, such as water residence time and ecological structure.

- Understanding of the interaction of physical forces, such as freshwater inflow and tidal actions and ecological structure, in mitigating the effects of nutrient enrichment, and how this may be influenced by climatic change and variability.

- Determination of the interactions of nutrient enrichment with other factors in controlling the dominance of benthos versus plankton algal species.

Understanding the Dynamic Interactions among Polluting Nutrients, Primary Producers, and Other Components of Coastal Ecosystems. Although there is abundant evidence nutrient enrichment affects the structure of coastal marine ecosystems, including fisheries ('top-down' control), and ecosystem structure, the system response to nutrient enrichment ('bottom-up' control), current understanding of the two influences is rudimentary. A better understanding of 'bottom-up' control of nutrient enrichment is necessary to estimate the societal and economic costs of eutrophication; better understanding of 'top-down' control could lead to better management of nutrient pollution (Nixon 1995; Cloern 2001; Rabalais 2002).

In regards to 'bottom-up' control of nutrient enrichment, the 'agricultural model' of Nixon (1995) suggests greater nitrogen inputs to coastal marine ecosystems lead to greater primary productivity rates and greater fishery productivity. Another model suggests that at higher trophic levels, productivity may increase to a point beyond which further enrichment leads to structural changes that lower secondary production (Caddy 1993). Thus, the quantitative relationship between nutrient loading and these changes, especially at higher trophic levels, is not well understood and may be related to the class of coastal environment.

'Top-down' control via grazing by zooplankton and benthic filter feeders has been shown to significantly influence the abundance and productivity of lacustrine phytoplankton. These grazers and filter feeders have been "implicated" as regulators of eutrophication in estuaries and coastal waters. Overfishing can cause cascading effects on trophic structure, leading to changes in grazing by zooplankton; there is speculation that in some coastal ecosystems declines in populations of benthic filter feeders (e.g., oysters and mussels) and overfishing may promote eutrophication because of a drop in grazing pressure on the phytoplankton. As with 'bottom-up' control, the quantitative impact of 'top-down' control on nutrient enrichment has received little research attention.

Important questions to consider include:

- To what extent is trophic structure altered by nutrient enrichment? Specifically, does nutrient enrichment lead to predictable changes in phytoplankton composition and the composition of benthic primary producers? Do these effects cascade up the food web?

- What are the relative influences of primary productivity and of trophic structure as regulators of fish and shellfish productivity? Are there predictable changes in the relative importance of these influences as nutrient enrichment increases?

- What is the quantitative importance of habitats that are sensitive to degradation during nutrient enrichment (e.g., seagrass beds) to fishery recruitment and productivity?

- What is the importance of benthic grazing and grazing by phytoplankton as regulators of phytoplankton biomass and productivity in coastal marine ecosystems, and how do these factors interact with physical controls on phytoplankton? To what extent can these 'top-down' controls counteract the effects of nutrient enrichment?

- Does grazing interact with nutrient enrichment to influence phytoplankton composition and the composition of benthic primary producers? Does this have consequences for organic matter sedimentation and bottom water dissolved oxygen concentrations, or for energy flow through the food web?

- How do these factors vary across different types of coastal marine ecosystems?

Understanding How Biogeochemical Cycling and Biological Community Dynamics Change During Periods of Eutrophication and Recovery. The sources and sinks of nitrogen, phosphorus, silica, and iron can be altered by eutrophication. For example, the adsorption of phosphorus onto both clastic sediments and tropical carbonate sediments may be lessened as ecosystems become more eutrophic. Bottom water anoxia may alter rates of denitrification, and whole-water column anoxia may favor planktonic nitrogen fixation. Eutrophication may increase iron availability, as sediments become more reducing, but silica availability may decrease due to greater sedimentation and/or slower decomposition in sediments. These changes in biogeochemical cycles may result in positive or negative feedbacks on eutrophication, and may alter the phytoplankton community composition and favor HABs. As changes in phytoplankton or zooplankton community composition accompany nutrient enrichment, altering the rate of sedimentation of organic matter, the concentration of dissolved oxygen in bottom waters is modified, further complicating changes in biogeochemical cycles. A better understanding of how biogeochemical cycles change during eutrophication, and during the recovery from eutrophication, is essential for making sound policy and management decisions about protection and restoration.

Key questions include:

- What changes does nutrient enrichment cause in the biogeochemical cycles within coastal marine ecosystems of elements such as nitrogen, phosphorus, silica, and iron, and how may these changes provide positive or negative feedbacks to eutrophication?

- How are changes induced from nutrient enrichment in biogeochemical cycles of nitrogen, phosphorus, silica, and iron related to salinity along an estuarine gradient, and how does this influence the sensitivity of a coastal marine ecosystem to nutrient pollution? How are these changes influenced by seasonal changes in salinity, and how might they respond to hydrologic changes associated with climatic change and variability?

- Are the changes that occur during nutrient enrichment similar across classes of ecosystems, or do some types of coastal marine ecosystems respond differently than others, due to differences in physical of ecological structure? What changes are associated with system changes from benthic to pelagic domination?

- Are there general changes during eutrophication in the nutrients that most limit production at either the annual or seasonal time scale? How might this effect the management of nutrient pollution in coastal systems?

- Once nutrient loads are reduced, how reversible are the changes in biogeochemical cycles?

- How do changes in biogeochemical cycles influence phytoplankton composition and HABs?

(2) Watersheds Draining into Impacted and Susceptible Coastal Waters

Assessment of Surface and Ground Waters, Riparian Zones, and Wetlands in the Watershed as Sources, Sinks, Conveyors, and Transformers of Nutrients. Most of the nitrogen used by humans is not exported to coastal ecosystems, but rather denitrified or retained where applied (NRC 2000). Only 20-25 percent of the nitrogen input to large watersheds is exported downstream in rivers; the rest is retained in soils and biomass or converted to nitrogen gas through the process of denitrification. Most denitrification probably occurs in surface waters, wetlands, and riparian zones, but some denitrification also occurs in soils, particularly wet, agricultural soils. A better understanding of nitrogen sinks is vital to better manage nutrient pollution so future changes can be anticipated. For instance, the accumulation of nitrogen in soil may slow over time as this sink becomes saturated, resulting in more downstream export of nitrogen. Also, denitrification in soils may increase or decrease when climate change alters soil moisture.

In general, the relative importance of denitrification compared to nitrogen being retained in soils and vegetation and accumulating in groundwater is poorly known, although both denitrification and retention are clearly important. The relative importance of the two processes varies among regions due to differences in climate, topography, and/or groundwater hydrology. For many regions, available data on nitrogen sources and sinks suggest that more than half the net nitrogen inputs from human activity are denitrified.

Many studies have shown that riparian zones and wetlands are major sinks of nitrate, with much of the nitrate probably being denitrified at the same time. Fewer studies have examined all inputs and outputs of nitrogen to riparian zones and wetlands, including fluxes of organic nitrogen. Denitrification also occurs readily in stream and riverbeds, lakes, and groundwater aquifers. The cumulative effect of this process across watersheds is very poorly estimated, however. Further research on the fate of nitrogen in wetlands, surface waters, and groundwater is necessary for the best management of coastal nutrient pollution. This research should be conducted in the context of whole watersheds.

Key research needs include:

- Investigating the role of groundwater in the nitrogen cycle of the watershed-coastal system. This includes analysis of the rate of accumulation of reactive nitrogen in aquifers as a temporary sink of nitrogen in the landscape and quantification of the rate at which nitrogen might be re-

injected to surface waters.

- Analyzing all forms of nitrogen in hydrologic fluxes through wetland, riparian zone, and surface-water ecosystems.

- Estimating the efficiency of riparian zones, wetlands, surface waters, and groundwaters as sinks of nitrogen through denitrification within large watersheds. This includes the effects of climate variability and change, including hydrologic changes, on sink effectiveness.

- Determining the importance of temporal patterns in fluxes, such as seasonal variations, in controlling sinks for nutrients in the landscape and how this might vary depending on climate, topography, and the size of the watershed.

- Measuring the production of nitrous oxide during denitrification and development of possible approaches for reducing the amount produced.

Quantification of the Inputs and Determination of the Fates of Nutrients under Different Land-Use Scenarios. The identification of nutrient sources is critical to managing nutrient pollution. Despite major progress over the past decade, there is still uncertainty about estimating the sources of nutrients draining from watersheds to coastal ecosystems. The uncertainty comes from incomplete or inaccurate knowledge about the inputs of nutrients to the watershed and a poor understanding of the fate of these inputs, particularly nitrogen.

For the United States as a whole, as well as in most individual estuaries, more nutrients come from non-point sources than from sewage and other point sources. While the fate of urban point sources is poorly known for many coastal ecosystems, our knowledge about these non-point sources is particularly poor. There is an urgent need to better understand nutrient sources from agricultural systems and from forests; the need for improved knowledge of nutrient sources in mixed-land-use types is particularly acute.

Atmospheric deposition of nitrogen, particularly onto land with subsequent export downstream, remains the most uncertain input of nitrogen to coastal ecosystems (NRC 2000). For some coastal ecosystems, deposition is clearly the largest source of nitrogen, while for others, it is minor. For many systems, estimates of the importance of atmospheric nitrogen input are quite divergent, including even some well studied estuaries, such as the Chesapeake Bay and the Hudson River estuary. Uncertainties about the rate of deposition and the fate of what is deposited onto the landscape contribute to the diverging estimates. Networks for determining atmospheric deposition are biased against sampling in near-coastal areas and near urban and agricultural sources of air pollution, exacerbating these uncertainties.

Recent research in small forested catchments suggests the details of disturbance and land-use history are critically important in determining how much nitrogen deposited from the air is retained in a forest versus exported downstream. Approaches are needed to evaluate the fate of nutrient deposition in forests at larger spatial areas, such as multiple catchments across a region or large watershed. Virtually nothing is known about the fate of nitrogen deposition in suburban areas or areas with mixed land-use.

Terrestrial ecosystems vary in the effectiveness with which they retain nutrients. Research could lead to a ranking of terrestrial systems for their potential to export nutrients to downstream ecosystems, and with regard to how climate change and land-use change may alter this export.

Important research needs include the following. *The first two are especially important.*

- Developing a better understanding of the availability of soil nutrients to crops; the efficiency of the timing, form, and placement of fertilizer and manure applications; and the relationship between fertilizer application rates and loss of nutrients.

- Developing advanced soil testing procedures to provide practical and reliable information about soil nutrients available to crops and their loss to surface and groundwater.

- Being able to better estimate NOx and ammonia deposition in near-coastal areas and close to emission sources.

- Particularly near emission sources, improving the estimates of dry deposition of both the oxidized and reduced forms of nitrogen.

- Analyzing organic nitrogen fluxes, including sources of organic nitrogen in deposition, and export of organic nitrogen from terrestrial ecosystems.

- Determining the effects of disturbance history in forests and analysis of nitrogen retention and export in forested catchments of various sizes.

- Determining the fate of nitrogen deposition in urban, suburban, and mixed-land-use areas.

- Analyzing the time trajectory of nitrogen accumulation from atmospheric deposition in the watershed, and how climate change and variation may influence nitrogen retention and downstream export.

- Improving ways of estimating atmospheric and groundwater fluxes of nutrients from agricultural systems, as well as fluxes of nutrients bound to particles.

- Establishing practices for reducing nitrogen leakage from animal feeding operations, including atmospheric fluxes.

(3) Predictive Modeling of the Watershed-Coastal System

Development of Predictive, Quantitative Models of Nutrient Inputs and Fluxes into and through the Watershed to the Coastal Ecosystem. Many models exist for estimating sources of nutrient inputs to watersheds and coastal ecosystems. These are critical tools for the manager charged with improving water quality. Many of these models have not been validated or verified with independent data, however, and using different models on the same watershed can yield very different estimates of nutrient sources.

Modeling research should develop a comprehensive, quantitative understanding of nitrogen cycling and transport in the landscape of large river basins and in any system that delivers nitrogen to sensitive coastal ecosystems. Presently, data from these models are not comparable or comprehensive. Improving these models is a critical element for efficiently reducing nutrient pollution in coastal ecosystems.

Many models do not include all major inputs of nitrogen, and often ignore the importance of

atmospheric deposition and inputs from animal feedlot operations. Most current models do not include nitrogen sinks in wetlands, riparian zones, and surface waters or respond to changes in management practices. Further, there is much spatial variation between models, some developed for relatively small areas, while others, for large watersheds or regions, with few, if any, efforts to compare the data between the two types.

Source modeling is also hampered by the data available for assessing nitrogen inputs nationwide in a consistent manner. A nationally, consistent database of nitrogen use, both from purposeful uses, such as agriculture, and inadvertent inputs, such as from fossil fuel combustion, would be extremely helpful in improving the models for estimating nitrogen fluxes to coastal ecosystems.

Overall, there is a fundamental need to develop and improve and validate quantitative models of nitrogen sources and fluxes through the watershed to the coast. Smaller-scale experiments and pilot projects testing effectiveness of both source controls and sink enhancements should be coupled with watershed-scale models that address nitrogen and phosphorus dynamics in agricultural areas. To make optimal use of both retrospective and prospective data, such efforts should include both hindcasting and forecasting exercises. To support managers, models must also be adaptable for changes in policies and practices.

Key considerations for model improvements include:

- Testing models through hindcasting and using them for forecasting.
- Validating models with data other than that used in their development and calibration.
- Including all major nutrient sources, fluxes, and 'sinks.'
- Developing databases of evaluations of the effectiveness of management practices against which models can be calibrated and validated.
- Making models responsive to climate change and variation.
- Comparing models developed for different spatial scales.
- Developing an accurate and consistent set of data on nutrient inputs to regions which can be used to drive models of export to coastal ecosystems.

Development of Mutually Informative Modeling and Observational Programs. To understand nutrient over-enrichment, we must acknowledge that the "development of process models for estuaries and open coastal systems is still in its infancy" (NRC 2000). Most models are site-specific, and generally quite simplistic in how they portray ecological and biogeochemical functions and feedbacks. The extensive research and monitoring data that exists could be used to improve the skill and general applicability of such models.

Development of more sophisticated models and models that are general enough for a range of coastal ecosystems would allow for integration of scientific understanding of nutrient enrichment and highlight key uncertainties. (Such models would also aid managers in setting goals for protecting and restoring coastal ecosystems.) More sophisticated process-based models are also essential to better understand nutrient pollution interaction with other stressors, including toxic substances, habitat loss, hydrologic alterations, overfishing, invasive species, and climate change.

Factors to consider in developing, verifying, and using such models include:

- An adequate, balanced representation of physical, ecological, and biogeochemical processes, with the benefit of simplicity and the danger of over-parameterizing a model.
- The relative importance of nutrient (e.g. 'bottom-up') control and predation (e.g. 'top-down') control of the interactions among primary producers and higher trophic levels.
- Biogeochemical feedbacks occurring during nutrient enrichment, including changes in organic sedimentation, phosphorus adsorption, denitrification, nitrogen fixation, and silica sedimentation.
- Responsiveness to climate change and climate variation.
- Explicit characterization of uncertainty, to the extent possible.
- Validating the model with different data than were used in the development and calibration.
- Funding from agencies for the development of databases used to calibrate and verify process models and develop statistical models.

(4) Strategies for Management of Impacted and Susceptible Coastal Ecosystems

Determining Societal Expectations. The degradation of coastal ecosystems by nutrient pollution is keenly felt in many regions, fostering a general increase in work to reverse coastal nutrient pollution. Restoring and protecting coastal ecosystems requires a clearer definition of societal goals for protecting them. In part, this entails a better understanding of how people use coastal ecosystems (either for work or pleasure) and how nutrient pollution affects those uses. More importantly, what Society perceives as desirable must be translated into scientifically measurable goals that become the basis of management.

Many questions arise when considering this. In most coastal ecosystems, efforts to control nutrient over-enrichment are based on indicators like dissolved oxygen concentrations or the area covered by seagrass beds. Yet, does raising dissolved oxygen levels and increasing the seagrass beds adequately protect what Society views as valuable? Rather, is it the loss of fish and shellfish, which are affected by lower levels of nutrient enrichment and the resulting loss of habitat quality in seagrass and kelp beds, or the alteration of ecological food-web structure? At what level does nutrient enrichment degrade aesthetic enjoyment of coastal ecosystems (via increased odors, lower water clarity, or increased HABs)? To what extent does Society value the loss of biodiversity that accompanies nutrient over-enrichment of coastal ecosystems?

Appropriate indicators of nutrient pollution that can be related to societal goals should be developed to protect coastal ecosystems. These indicators and goals should also directly relate to nutrient loads, so specific targets for nutrient reduction can be set. These may become a basis for the TMDL or other load-based management strategies.

Critical research needs to determine social impacts and to better relate societal goals to measurable

management goals include:

- Better assessment of the ecological damage to fish and shellfish resources, including damage resulting from degradation of habitat quality.
- Exploration of a broader range of environmental impacts to be used as the basis of analysis of social and economic impacts, including potential impacts on biodiversity, on ecosystem goods and services, and on aesthetic enjoyment of coastal systems.
- Assessment of the trajectory of change from nutrient enrichment in coastal systems, including changes in dissolved oxygen, seagrass and kelp beds, habitat quality, and community composition and food-web structure and of how scientifically measurable changes relate to the criteria most important to society.
- Development of indicators of nutrient pollution that directly relate to goals for the protection and restoration of coastal ecosystems that are important to society.

Development of Optimal Policy and Management Strategies to Maximize the Benefits and Minimize the Costs of Nutrient Reduction. Nutrients come from many sources in the landscape, and a variety of approaches are possible for their reduction. These include voluntary approaches based on education and good citizenship or fear of regulation, as well as approaches based on subsidies and financial incentives, technology-based regulation, and implementing marketable permits for achieving permissible loading levels.

Incentives can also be used to create or restore wetlands and riparian buffers to reduce nutrient flux to coastal ecosystems. The best approach may be a hybrid, using different approaches for different sources of nutrients in different settings, but more knowledge is needed on how to best target different approaches to specific problems. Management decisions should be driven by the best available research on the relative efficacy of these various policy options. If management relies on economic approaches, better estimates of the costs for reducing nutrient fluxes from a variety of possible sources (and for using a variety of approaches) are required.

Key questions to consider include:

- In addition to reducing nutrient pollution to coastal ecosystems, what ancillary benefits to society or the environment accrue from various management options, and how can such benefits best be documented and measured?
- What cultural, legal, regulatory, or economic impediments exist for various management and policy options?
- Can optimization procedures be developed for the application of complex, hybrid policy approaches necessary for reducing nutrient pollution?
- How might future changes in agricultural policies, technologies, or international agricultural markets affect policies for reducing nutrient pollution from agroecosystems?
- How might future changes in energy policy affect policies for reducing nutrient pollution from agriculture and fossil fuel combustion?

Development and Evaluation of Effective and Innovative Approaches to the Management of Nutrient Inputs to Coastal Waters. A variety of approaches exist for reducing nutrient loads to coastal ecosystems. These include BMPs for farms and construction projects, technologies for human waste disposal, and creation of wetlands to increase the sink for nutrients in the environment. Even better approaches could be developed, however. Many treatment technologies and management practices were designed to address phosphorus pollution; since nitrogen is more mobile in both groundwater and the atmosphere, these practices and technologies often need to be refined or altered. Also, there is an urgent need for independent evaluation of various practices, approaches, and technologies.

For the United States as a whole, agriculture is the largest source of nitrogen pollution to coastal waters, although its contribution to individual coastal ecosystems varies greatly (NRC 2000). Both losses to surface and groundwater from agricultural fields and emissions from animal manure are major contributors of nitrogen pollution. Research could result in better management practices for reducing nutrient export from agricultural fields. Other pertinent research includes biological nitrogen fixation, in-field denitrification, and other factors regulating availability of soil nutrients to agricultural crops, site-specific techniques to improve the efficient use of fertilizer and manure applications, and (especially) the relationship of fertilizer application rates and timing to loss of nutrients to surface waters in different settings. Important issues to consider while conducting such research are the type of crops grown, subsurface drainage, and type of tillage. Much of this research can, and should, be conducted on small agricultural plots, but methods are needed for applying the results to larger watersheds, including watersheds with mixed land-use. The influence of climate change and variability on fluxes of nutrients from agricultural systems also needs specific study.

The contribution of construction site erosion and sedimentation in flood zones can be significant and is a Federal issue when construction is covered by Federal flood insurance. Presently, review of proposals for construction permits helps to ensure that shoreline construction activities are compatible with river management activities, including flood control, navigation, land use, recreation, power generation, and water quality. Research could improve BMPs delineating proper installation, maintenance, inspection, and removal of temporary erosion and sediment controls.

For wastewater treatment, there has been remarkably little innovation for municipal treatment plants over the past several decades (NRC 1993b). Research on new approaches for cost-effective nutrient removal should be encouraged. In many coastal areas, human wastes go through septic systems at individual homes. In general, these are poor at removing nitrogen, and septic wastes are a major source of nutrient pollution to many coastal ecosystems. Research on innovative technologies and independent assessment of these efforts is highly desirable. Constructed wetlands most likely will play an important role in the future for wastewater treatment and for reducing nutrient pollution from both agricultural sources and atmospheric deposition. Research should focus on the evaluation of the effectiveness of these systems and on approaches for increasing their effectiveness.

Important research needs include:

- Developing management practices to reduce nitrogen losses to the atmosphere and to groundwater from animal manure, particularly for waste from concentrated animal feeding operations.
- Analyzing the loss of nutrients from agricultural fields in the context of soil, climate, slope, and agricultural practices, building towards a general classification scheme for ‘leakiness’ of fields and the responsiveness to proper management, including cropping, tillage practices, and drainage.
- Developing fertilizer application technologies to increase efficiency and reduce loss to the

environment.

- Developing practical and effective construction practices sequencing.

- Evaluating management practices and systems at the watersheds and airsheds level.

- Developing new treatment technologies for human wastes at different levels: large sewage systems, small neighborhoods, and individual homes.

- Using wetlands as treatment systems for human and animal waste and as an approach for increasing the nutrient sink from atmospheric deposition and agricultural pollution.

- Independently assessing the effectiveness of management practices and technologies for reducing nutrient pollution.

The Role of Federal Agencies

The NRC's *Clean Coastal Waters* report (2000) called for a national strategy to reduce nutrient pollution in coastal waters. One of the Report's key recommendations was, "Federal agencies should exert Federal leadership on issues that span multiple jurisdictions, involve several sectors of the economy, threaten federally managed resources, or require broad expertise or long-term effort beyond the resources of local and state agencies." In doing so, the Council recognized the need for a strong Federal role in combating nutrient pollution and hypoxia, because the sources of nitrogen affect watersheds cut across many states and are drained by major rivers flowing into coastal waters. Figure 10, from that report, further depicts why it is essential to coordinate the Federal agencies and the political realm, in hand with the physical/chemical/biological efforts to reduce nitrogen pollution.

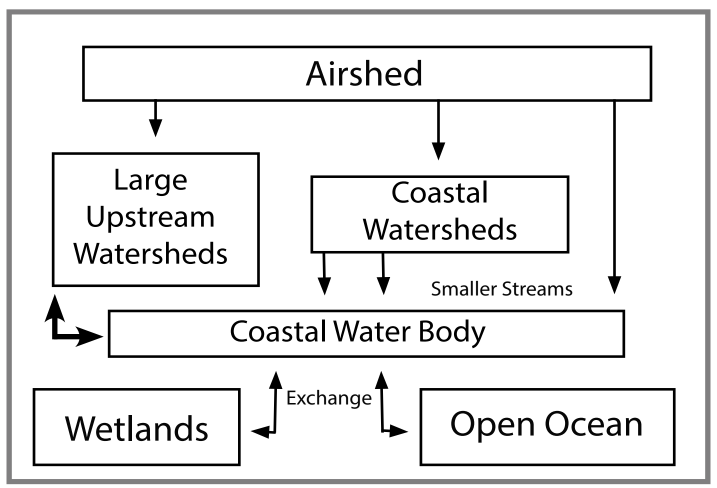


Figure 10. Each of these areas is managed by a different Federal agency. (Adapted from the Clean Coastal Waters report, NRC 200)

Interagency Managing of Resources and Information

Since watersheds are geographically associated with multiple jurisdictions and Federally-managed resources, Federal involvement is unavoidable. A coordinated action plan to monitor, understand, and manage coastal eutrophication requires Federal leadership. This is all the more important because nutrient management is certain to impact several sectors of the economy, all which have highly disparate goals, and to further burden these sectors with the additional costs of mitigation practices. Routine, long-term monitoring of watershed and coastal ecosystems also requires a commitment to provide the necessary resources to initiate and sustain the infrastructure and broad expertise beyond the resources of state and local agencies (NRC 2000).

Because the distribution of congressionally mandated missions among Federal agencies cannot realistically be expected to anticipate every possible situation, gaps in existing and proposed Federal programs dealing with nutrient over-enrichment must be identified. A framework for interagency communication and cooperation must be developed to avoid duplication of effort and incompatibilities of research and management objectives. Communication, coordination, and cooperation are also vital to ensure that important problems do not go unnoticed and unattended because they do not fit neatly into any one agency's jurisdiction.

Finally, although the foregoing recommendations for reducing uncertainties in our understanding of coastal eutrophication and hypoxia and of their sequelae are scientifically sound and realistic, investments in science and technology by the Federal government will certainly be required. Again, this involves communication, coordination, and cooperation across several agencies to promote a linked program of monitoring, research, modeling, education, and adaptive management. Within the government, research programs, monitoring activities, technical expertise, and infrastructure of NOAA, USDA, EPA, and USGS should be organized in a new partnership to provide the fundamental information links among the high-altitude drainage basin to the open coast. Partnerships among agencies should be firmly established to provide support and technical expertise for regional scale satellite observation of entire watershed-coastal systems and to tap into the expertise of the United States academic research community. However, all of the above activities will have to be considered in light of budget constraints and agency priorities.

Avoiding Duplication of Efforts

Presently, coordination of science efforts and activities at the Federal level occurs primarily through the National Science and Technology Council (NSTC). Through this Cabinet-level Council and its various subcommittees, the President coordinates science, space, and technology across the diverse parts of Federal research and development. The Committee on Environment and National Resources (CENR), a committee of the NSTC, provides the primary mechanism to avoid duplication of Federal efforts in the areas of science and technology research and development.

The members of this committee are from agencies involved in addressing hypoxia and eutrophication and include the Department of the Interior (via USGS), the EPA, the Department of Commerce (via NOAA), and the USDA. In addition, budget resource allocation, tracking, and coordination come through the Office of Management and Budget (OMB), working closely with the Office of Science and Technology Policy (OSTP) and the NSTC.

Nutrients, particularly nitrogen, pose the largest pollution threat to the estuaries of the United States.

Conclusions

There are a variety of sources of nitrogen, including natural sources, runoff from agricultural fields, concentrated animal feeding operations, atmospheric deposition of NO_x from fossil fuel combustion, and sewage and septic wastes. While the relative contributions of these sources vary among watersheds, non-point sources from agriculture and the atmosphere are most often the most significant contributors. Total nitrogen inputs to estuaries and coastal waters are increasing and, if current trends continue, loading in 2030 is projected to be 30 percent higher than current levels, more than twice what it was in 1961.

Negative effects of excessive nutrients, such as algal blooms and hypoxia, have been observed in a significant number of the Nation's estuaries (Figure 11). Again, trend data are limited, but there is some evidence that conditions have worsened in many estuaries since the 1970s, and given the projected increase in loads, eutrophic conditions are expected to worsen. Estuarine ecosystems degraded by eutrophication show diminished economic and environmental value, including negative impacts on boating, fishing, and tourism and declines in economically important fish and shellfish populations.

Figure 11. A bloom of nuisance algae mars an estuary in the state of Washington. (Photo courtesy of Puget Sound Water Quality Action Team).

The most effective approach to managing this issue is one that targets the protection of healthy ecosystems and restoration of damaged ones. Technical tools for reducing nitrogen pollution already exist at reasonable cost and should be applied in adaptive and flexible ways, built around the watershed approach. In cases where watersheds include lands from multiple states, multi-state coordination and Federal support will be necessary. While this watershed approach, including nutrient trading, is preferred in many cases, national or regional approaches may be more effective for controlling more distant sources, such as atmospheric deposition from fossil fuel combustion.

While current scientific knowledge is sufficient to address many of the coastal nitrogen pollution issues, progress will be quicker and more cost effective if key uncertainties are addressed. Three key areas requiring attention are: developing a more comprehensive monitoring program to take advantage of existing programs and explore real-time data acquisition and remote sensing monitoring approaches, improving models of the movement of nutrients through watersheds in response to natural and human activities, and developing estuarine susceptibility models capable of forecasting the impact of changes in nutrient loads.

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Appendix A - Federal, State, and Local Laws and Programs

There are a variety of legislative and programmatic tools that can be used to control hypoxia. These range from mandatory Federal programs, to voluntary local initiatives, and are described below.

Federal Laws and Programs

The Clean Water Act (CWA)

The original 1948 statute (Ch. 758; P.L. 845), the Federal Water Pollution Control Act, as amended by the Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500), stipulates broad national objectives "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The Water Quality Act of 1987 (P.L. 100-4) provides the most recent series of amendments to the original statute and addresses water pollution source management and control programs, from both point sources (discrete outfalls or discharges) and non-point sources (runoff or diffuse pollution), and on a watershed basis.

Point sources are regulated through the National Pollutant Discharge Elimination System (NPDES), which establishes permit requirements that include numerical limits on the amount of pollution

discharged. Section 402 of the 1972 amendments established the NPDES to authorize the Environmental Protection Agency (EPA) issuance of these discharge permits (33 U.S.C. 1342). The EPA has delegated authority for the NPDES program to almost all of the states, and therefore, the States establish the water quality standards and typically administer permits for sewage treatment plants, factory outfalls, and large confined animal feeding operations. These standards provide an enforceable means to ensure that water pollution is reduced over time, and as new standards are developed, that permits are revised and discharge limits adjusted to meet clean water goals.

The CWA addresses non-point or diffuse sources of pollution that originate as runoff through Section 319, which establishes a requirement that states develop and implement statewide non-point source management programs. Though these programs are not strictly enforceable, they include actions states will take to address a wide range of sources of polluted runoff, including agriculture, forestry, mining, and urban stormwater. States receive grants from the EPA to implement their programs. Currently, the States are revising their non-point source management programs to meet nine key elements identified by the EPA as necessary to upgrade and improve their effectiveness. Failure to adequately address these nine key elements could result in loss of eligibility for significant increases in Federal dollars to implement Section 319 programs.

Under Section 303(d), states are required to identify and list those waters that fail to achieve water quality standards and to develop total maximum daily loads (TMDLs) for them. The TMDLs establish the pollutant loads necessary to achieve water quality standards, and thereby, provide a basis for further limits on pollution from both point and non-point sources. Development and implementation of TMDLs provides an additional tool for ensuring that water pollution loads are reduced, working to minimize the potential for hypoxia events.

***The Clean Water Act Section 305(b) and 303(d) Assessments**.* Of the 29 coastal states and territories, 27 rated general water quality conditions in some of their estuarine waters. Together, these states assessed 31,072 square miles of estuarine waters, which equals 36 percent of the 87,369 square miles of estuarine waters in the Nation. Of the 29 coastal states and territories, 15 rated general water quality conditions for ocean shoreline. They assessed 3,221 square miles, representing six percent of the Nation's coastline (if the 36,000 square miles of coastline in Alaska are included); 14 percent of 22,618 square miles of national coastline sans Alaska.

States and territories reported that some form of pollution or habitat degradation impairs 51 percent of assessed estuarine waters. Of these impaired estuarine waters, 12 percent (1,929 square miles) are impaired by nutrients[5], and 34 percent (5,324 square miles) are impaired by organic matter enrichment and/or low dissolved oxygen.

States and territories reported that some form of pollution or habitat degradation impairs 14 percent of assessed coastal waters. Of these impaired coastal waters, 10 percent (43 square miles) are impaired by nutrients, and 24 percent (102 square miles) are impaired by organic matter enrichment and/or low dissolved oxygen.

Included in the 1998 303(d) list of impaired waters are 56,250 stream miles and 1,480,000 lake acres located in the coastal watersheds of the conterminous United States. Of these impaired waters, 15,080 stream miles (27 percent) and 720,000 lake acres (49 percent) are impaired by nutrients, while 14,000 stream miles (25 percent) and 615,000 lake acres (42 percent) are impaired by organic matter enrichment and/or low dissolved oxygen.

The Clean Water Action Plan. In 1997, the 25th anniversary of the Clean Water Act, the United States Department of Agriculture (USDA) and the EPA were directed to work with other Federal agencies and the public to prepare an aggressive Action Plan to meet the promise of clean, safe water for all Americans. The Clean Water Action Plan (CWAP) was published in February, 1998, and establishes a framework for implementing many of the existing clean water programs described above. In addition, the CWAP identified 111 'key actions' to strengthen efforts to restore and protect water resources. Several key actions have particular relevance for reducing inputs that lead to hypoxia:

- The EPA was to publish criteria (i.e., scientific information concerning levels of a pollutant) for nutrients by 2000. These criteria will be used by states to develop numeric nutrient provisions of state water quality standards.

- States and tribes have worked together with the public to develop Unified Watershed Assessments, identifying those watersheds that do not meet water quality and other natural resource goals. For priority watersheds, states are now developing Watershed Restoration Action Strategies to identify the necessary actions to restore waters to their designated use, including reductions in nutrient pollution that leads to hypoxia.

- The USDA and the EPA have released a joint Unified National Animal Feeding Operations Strategy to minimize the environmental and public health impacts of Animal Feeding Operations.

A fundamental principle of the Clean Water Action Plan is to address water resource problems through a watershed approach, ensuring that priorities are established and actions taken in a comprehensive fashion to clean up rivers, lakes, and coastal waters.

The Coastal Zone Management Act (CZMA)

The Coastal Zone Management Act Of 1972, as amended through P.L. 104-150, The Coastal Zone Protection Act of 1996, establishes a Federal-State partnership for managing the Nation's coastal resources. The CZMA is administered by the National Oceanic and Atmospheric Administration (NOAA). Participation is voluntary.

The program focuses on balancing competing land and water uses while protecting sensitive resources. States meet Federal requirements to gain approval of their CZM programs, after which, they receive grants from the NOAA for program implementation. State CZM programs offer the ability to focus on the cumulative and secondary impacts of development in coastal areas and to develop special area management plans to balance growth with resource protection.

Of particular relevance for reducing inputs that lead to hypoxia is Section 6217, entitled "Protecting Coastal Waters," added by Congress to the CZMA in 1990. This Section requires states with approved coastal zone management programs to develop Coastal Non-point Pollution Control Programs. In keeping with the successful Federal-State partnership to manage and protect coastal resources achieved by the CZMA, Section 6217 envisioned that non-point source programs developed under Section 319 of the CWA would be combined with existing coastal management programs. By combining the water quality expertise of state 319 agencies with the land management expertise of coastal zone agencies, Section 6217 is designed to more effectively manage non-point source pollution in coastal areas.

Twenty-nine coastal states and territories have developed coastal non-point programs and are beginning to implement them. These programs include management measures for each of the major

non-point source categories that impact coastal waters, including agriculture, forestry, urban sources, marinas, and hydromodification. Implementation of these management measures will reduce sources of non-point pollution contributing to hypoxia.

The Farm Bill

The Farm Security and Rural Investment Act of 2002 (FSRIA; P.L.107-171) is landmark legislation for conservation funding and for focusing on environmental issues. The chief programs in the 2002 Farm Bill that relate to water quality improvements are described below. The largest programs are the Environmental Quality Incentives Program (EQIP) and the Conservation Reserve Program (CRP). In the 2002 FSRIA, the EQIP, which provides technical and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns, received a $4.6 billion increase over a six-year period, the largest increase in funding of all the Farm Bill programs. The EQIP contains several provisions, including to provide cost-share funding for large, confined animal feeding operations; to target funds toward livestock operations (60 percent livestock operations, 40 percent non-livestock operations); to establish a national water conservation program, providing incentives and cost-share funds for surface and groundwater conservation; and to establish a Conservation Innovation Grants Program to encourage innovative approaches to leveraging Federal investments in environmental enhancements and protection. The recently promulgated EQIP regulations include four national conservation priorities, including the reduction of non-point source water pollution and of soil erosion and sedimentation from unacceptable levels on agricultural lands. The priorities will be used to rank applications and award EQIP contracts.

The second largest Farm Bill program, the CRP, provides rental payments to farmers in exchange for establishing long-term ground cover on up to 39.2 million acres of environmentally sensitive lands. The CRP includes the Conservation Reserve Enhancement Program and the CRP Buffer Initiative and gives priority to soil erosion control, water quality, and wildlife habitat. In addition, all states are now eligible to participate in the Farmable Wetlands Pilot Program, allowing farmers to enroll small acreages of wetlands within fields into the CRP.

There are several smaller Farm Bill programs that directly address water quality and wetlands. The Wetlands Reserve Program (WRP) has more than doubled to 2.275 million acres in the latest Farm Bill. The WRP allows producers to restore and enhance additional acreage of cropped wetlands in exchange for cost-share and/or easement payments. Another program dealing with wetlands is the Wildlife Habitat Incentive Program (WHIP). The WHIP encourages landowners to develop critical wildlife habitat, especially for threatened and endangered species and fish, through cost-share payments and 30-year and permanent easements. Another program specific to water quality, the Great Lakes Basin Program for Soil Erosion and Sediment Control, authorizes the Secretary of Agriculture, in conjunction with the EPA and the Army Corps of Engineers, to provide grants for project demonstration and technical and educational assistance in the Great Lakes Basin related to improving basin water quality via soil erosion and sediment control.

In addition to the programs described above, several programs address conservation of working lands. The Conservation Security Program (CSP) is a new program established in the 2002 Farm Bill to provide payments to producers as incentives or cost-sharing to adopt or maintain conservation practices on private working lands. Producers who enroll in the CSP will implement their choice of three tiers of increasingly complex conservation practices and systems. The Farmland and Ranchland Protection Program provides cost-share funds in conjunction with states to purchase conservation easements to prevent conversion of agricultural lands to other uses. The Grassland Reserve Program (GRP) is a new program using both short-term (10-, 15-, or 20-year rental agreements) and long-term (30-year and permanent easements) contracts to restore and protect two million acres of grasslands, including small tracts (< 40 acres) of native grasslands. A conservation plan approved by the Natural Resources Conservation Service (NRCS, USDA) is required for those who enroll in the GRP. The Conservation of Private Grazing Land Program (CPGL) is now incorporated into the 2002 Farm Bill and is carried out by conservation districts. The CPGL provides for technical assistance to improve and manage private grazing lands. Included within the Forestry Title of the 2002 Farm Bill is the Forest Land Enhancement Program (FLEP). The FLEP is a new cost-share program that will be implemented by state foresters to provide financial, technical, and educational assistance to private, non-industrial forest landowners.

The Clean Air Act (CAA)

The Clean Air Act of 1970 (42 U.S.C. s/s 7401 et seq.) regulates air emissions from area, stationary, and mobile sources. Under the CAA, the EPA is authorized to establish National Ambient Air Quality Standards to protect public health and the environment. As airborne nitrogen has become an increasing concern for air deposition to surface waters, the CAA offers a tool to further control nitrogen emissions. These programs, authorized under Title I of the CAA, reduce NOx, as well as other pollutants, and are primarily implemented at the state level. Title IV, the Acid Rain Cap and Trade Program of the CAA Amendments of 1990 (P.L. 101-549), was created to reduce the adverse effects of acid rain deposition by reducing and limiting the rates of NOx and sulfur oxide emissions from electric utilities. The implementation of this program may reduce NOx emissions from both electric utilities close to the coast, as well as those much farther inland.

State Laws and Programs

Many state laws and programs are based on the Federal statutes and programs identified above. State water permitting and statewide non-point source programs are derived from the CWA; state agricultural programs, from the Farm Bill, and state coastal management and coastal non-point programs, from the CZMA and Coastal Zone Act Reauthorization Amendments. In addition, many states have enacted their own laws and developed state-specific programs to address particular natural resource issues.

For example, Maryland's Water Quality Improvement Act was developed in response to outbreaks of *Pfiesteria piscicida* (a toxic algae) and designed to reduce nutrient pollution from agricultural sources which precipitate HAB events. Oregon's Senate Bill 1010 was enacted, in part, to develop agricultural water quality management plans that will reduce impacts to salmon. These, and other state initiatives, provide an array of applications to further reduce sources of pollution that lead to hypoxia. In addition, many states have augmented Federal dollars with their own cost-share and grant programs to support local water pollution and watershed management initiatives.

Local Programs and Initiatives

In addition to Federal and state efforts, many local governments have developed ordinances and special initiatives to reduce pollution. Most important, local governments are typically responsible for managing growth and development through planning and zoning and other land-use controls. With population growth and increasing development in United States coastal areas posing one of the greatest threats for future coastal water quality problems, growth management and resource protection at the local level will become even more important.

As with states responding to Federal mandates, local governments often implement management activities in response to State law or policy. State erosion and sediment control laws and stormwater management programs are important drivers for local, urban runoff control efforts. Many local governments require site plan reviews, erosion and sediment control plans, and post-development stormwater management as conditions of approval for new construction activities. These tools ensure expanding land development does not degrade clean water or further exacerbate existing water quality problems.

Glossary and Acronyms

Adaptive Management - Systematic and rigorous approach to learning from the outcomes of management actions, accommodating change, and improving management.

Aerobic - Living, active, occurring, or existing only in the presence of oxygen.

Agroecosystem – An ecosystem where watershed land-use is primarily agricultural.

Airshed – The land area affected by airborne pollutants, particularly nitrogen. This can span long distances depending on the source of the emission.

Algae – Aquatic plants, whether marine or freshwater, usually chlorophyll-containing and nonvascular. They can be attached or free-floating. Algae constitute a main group of primary producers.

Algal Bloom – The rapid, excessive growth of algae, generally caused by high nutrient levels and favorable conditions. This can result in deoxygenation of a water mass when the algae die, leading to the death of oxygen-dependent aquatic flora and fauna.

Anaerobic - Living, active, occurring, or existing in the absence of free oxygen.

Anoxia – Hypoxia of extreme severity, wherein dissolved oxygen is nearly or completely absent (i.e., below 1 mg/L) from portions of a waterbody, causing physiological stress, and sometimes, death to aquatic organisms.

Anthropogenic – Human and culturally derived (non-natural) impacts on natural systems. In this report, it is impacts on eutrophication.

Atmospheric Deposition - Chemical compounds containing nitrogen or phosphorus settling onto the land or water surface. Both wet and dry deposition can occur.

Benthic (Benthos) – The fish, invertebrates, and other animals that live on/in the mud, rocks, and other material forming the bottom substrate in water bodies.

Benthic Primary Producers – The plants that live on the substrate below the water surface.

Benthic Filter Feeders – Those animals that live attached to the rocks and other substrate under the water and obtain food by filtering the water, such oysters and clams.

Biodiversity – Biological diversity in an environment as indicated by numbers of different species of plants and animals.

Biogeochemical Reactions (Processes) – The partitioning and cycling of chemical elements and compounds between the living and nonliving parts of an ecosystem. For example, the uptake of nutrients by phytoplankton.

Biogeochemical Cycles – Biogeochemical processes that are cyclic. A good example is the nutrient cycling by phytoplankton during production of organic matter. Phytoplankton take up nutrients during photosynthesis. When they die, this organic matter falls to the bottom and is consumed or broken down, releasing nutrients to the water column, which can then be taken up once more by phytoplankton during photosynthesis.

Biogeochemical Feedback – End outcomes of biogeochemical processes that alter the rate of initiation of these same processes. For instance, oxygen is needed for conversion of ammonia to nitrate and nitrite. If all oxygen is consumed, the conversion process stops.

Biological Oxygen Demand – Amount of oxygen required for the degradation of organic matter by microorganisms.

Biologically Stressful Oxygen Concentration - Dissolved oxygen levels greater than 2 mg/L but less than 5 mg/L that can cause physiological stress to aquatic organisms; below what is needed to meet the *Biological Oxygen Demand*.

Biomass – A general term referring to the amount of living material produced per unit area or volume. This may be expressed as grams of carbon or total dry weight.

Bioretention – The ability of plants and animals to retain or keep material in the system. Within the scope of this report, bioretention implies the preservation of nutrients/pollutants in the watershed, thereby preventing them from entering the estuary.

BMP – Best Management Practices. Actions to keep soil and other pollutants out of aquatic systems, especially streams and lakes. The BMPs are designed to protect water quality and to prevent new pollution. This applies to agriculture and other land-uses that disturb the land and cause runoff in tributary streams – buffer strips, hay bale barriers, etc.

Bottom-up Control – “The very small drive the very large;” It is the nutrient supply to the primary producers that ultimately controls how ecosystems function.

CAFO – Concentrated animal feeding operations. Agricultural operations where animals are kept and raised in confined situations. Animal waste and wastewater can enter water bodies from spills or breaks of waste storage structures (due to accidents or excessive rain), and non-agricultural application of manure to crop land.

Catchment – An area that “catches” water, such as a drainage basin or watershed.

CENR - Committee on Environment and Natural Resources Research. Advises and assists the NSTC to increase the overall effectiveness and productivity of Federal R&D efforts in the area of the environment and natural resources.

Chlorophyll *a* – The organic compound (pigment) that makes plants green.

Conservation Buffers - Small areas or strips of land in permanent vegetation (e.g., field borders, filter strips, grassed waterways, riparian zones, and wetlands) designed to slow water runoff, provide shelter, and stabilize riparian areas. Strategically placed, buffer strips in the agricultural landscape can effectively mitigate the movement of sediment, nutrients, and pesticides within farm fields and from farm fields.

Constructed Wetland – A non-natural wetland; one that is man-made.

CSO – Combined sewer outfall. Stormwater and treated sewage flow through the same outfall. During periods of heavy rain, inadequately treated sewage may be released.

Denitrification – The process of removing nitrogen or nitrogen compounds (e.g., nitrate and nitrite) from a substance via conversion to nitrogen gas.

Detention – Holding water in an area or slowing its flow rate out of the system.

Dissolved Oxygen - The amount (concentration) of oxygen that is dissolved in water.

DIN – Dissolved inorganic nitrogen. The inorganic (i.e., not derived from living organisms) forms of nitrogen - principally nitrate, nitrite, and ammonia.

Drip Irrigation – Watering of plants on a large scale using a hose or other system that allows for ‘drips’ of water rather than sprinkling.

Epiphyte – A plant that grows usually on surfaces of other plants or objects. As in *Epiphytic Algae* – Algae attached to the surfaces of substrates, such as shells of living clams and oysters, or other plants, such as submerged aquatic vegetation.

Estuarine Susceptibility – How easily an estuary can be affected by a given factor. In this report, estuarine susceptibility refers to the sensitivity of an estuary to develop water quality problems related to nutrient enrichment.

Estuary - A semi-enclosed body of water with an open connection to the sea and within which seawater is diluted with freshwater that is derived from land drainage.

Eutrophication – An increase in the rate of supply of organic matter (i.e., nutrients), either from external sources or from production within the system through biological processes. If extreme, it

can promote algal blooms, and the subsequent die-off of the plants and resulting over-production of organic matter, may further lead to secondary symptoms, such as hypoxia.

Filtration – A fluid passing through a substance or area; permeation of a barrier.

Food Web – The network describing the feeding interactions of the species in an ecological community.

HAB - Harmful Algal Bloom. Algal blooms that create noxious odors or release toxic compounds (i.e., toxic blooms), which are detrimental to animal (including human) health.

Hydrologic Units – Subdivision of the United States into smaller geographic areas representing part of all of a surface drainage basin, a combination of drainage basins, or a distinct hydrologic feature.

Hydromodification – Changes in the circulation patters of water or the delivery of water.

Hypoxia – A depletion of dissolved oxygen in the water column to below 2 mg/L, which can stress associated aquatic organisms.

Impervious Surface – Any material that substantially reduces or prevents the infiltration by water. It includes surfaces, such as compacted sand, lime rock, or clay, as well as most conventionally surfaced street, roofs, sidewalks, parking lots, and other similar structures.

Index of Biotic Integrity - An index that measures the biological 'health' of an area or water body.

Infiltration – To filter into or permeate a substance, place, or barrier.

Lacustrine – relating to, formed in, living in, or growing in lakes.

Low Impact Development - Designing development to reduce the standard impacts on the surrounding environment.

Macrophytes – Large algae that are attached to the bottom substrate of a water body. Generally, these are considered 'sea weeds'.

MRB – Mississippi River Basin. The entire drainage area of the Mississippi River System.

MSEA – Management Systems Evaluation Areas. Network of research and education projects established by the U.S. Department of Agriculture examining the impact of farming systems on water quality and developing profitable cropping systems that also protect water resources.

Net Anthropogenic Nitrogen Inputs - Those nitrogen inputs that are human and culturally derived (non-natural), including nitrogen harvested from crops and pastures, from fertilizers, by nitrogen gas fixation, by atmospheric deposition (wet and dry), and from animal manure.

Nitrification – The conversion of ammonia, a biological byproduct or waste, to biologically reactive forms of nitrogen (nitrate and nitrate). These are taken up by plants to sustain and promote growth.

Non-point Sources - Any source of water pollution that is not *Point Source*, primarily diffuse runoff.

NOx – Oxidized Nitrogen Emissions. Formed during combustion when molecules of nitrogen and oxygen from the air are combined with vehicle fuel. They contribute to the formation of acid rain, smog, and ozone at low altitudes.

NSTC – National Science and Technology Council. Cabinet-level Council serving to coordinate science, space, and technology across the diverse parts of the Federal research and development efforts.

Nutrient Load – Total amount of nitrogen or phosphorus entering the water during a given time, such as "tons of nitrogen per year." Nutrients may enter the water from runoff, groundwater, or the air. In this report, it is more specifically addressing nitrogen loading.

Organic Matter – Material derived from living organisms.

OSTP – Office of Science and Technology Policy. Was created to provide the President with timely policy advice and to coordinate the science and technology investment.

OWTS – Onsite Wastewater Treatment Systems. Almost always, these are septic systems on parcels of private land.

Pelagic – Organisms living in the water column seaward of the shelf-slope break (i.e., oceanic).

Phytoplankton – Microscopic photosynthesizing organisms (i.e., plants) that reside in the water column.

Planktonic Algae – Algae that are passively floating or drifting in a body of water.

Point Sources - Any discernible, confined, and discrete route (e.g., pipe or concentrated animal feeding operation) from which pollutants are or may be discharged.

Primary Production – The biomass resulting from green plants converting sunlight into living (organic) material.

Residence Time - Average time a substance spends in a water body before removal.

Riparian Zones – A strip of land between the river channel and its floodplain, which directly influences or is influenced by the body of water.

SAV – Submerged Aquatic Vegetation. The underwater grasses that live in shallow waters. These include eelgrass.

Secchi Depth – The depth of water at which a Secchi Disc can no longer be seen. A Secchi Disc is a round disc with quadrants painted black and white. It is lowered into the water and the depth marked where it can no longer be seen. It is a measure of water clarity; the deeper its visibility, the clearer the water.

Secondary Production – The amount of organic material incorporated by animals from food per unit area over time.

Secondary [Waste] Treatment - Process in which bacteria degrade most of the organic matter in the waste. The resulting quality of water depends on how much it was treated.

Sink – A device or system that keeps something within a given area, thereby preventing it from doing damage to another area. In this report, a nutrient sink in biological systems holds nutrients within a wetland and/or submerged grasses and epiphytic plankton, preventing them from transport elsewhere where they might contribute to eutrophication.

Soil Permeability – The water retained by the soil versus the amount that is released and flows elsewhere.

SSO – Sanitary Sewer Overflows. A separate sanitary sewer system designed to transport a range of domestic, institutional, and industrial wastewater to a terminating treatment facility. As a general rule, a sanitary sewer is designed to convey 100% of all wastewater to a treatment facility and does not contain special outlets or diversion structures to allow overflows from the sanitary sewer.

Stratification – Layers of water that do not mix due to density differences caused by temperature or salinity differences. Stratification commonly occurs in large bodies of water as the surface is heated by the sun through the spring and summer or where freshwater flows into a saline water body. Stratification can promote low dissolved oxygen conditions (i.e., hypoxia/anoxia) in bottom waters, because there is no resupply of oxygen to bottom waters as it is consumed by the respiration of plants and animals or by the rotting of organic matter.

Tile Drainage - The diversion of the top of the water table into underground drainage tile lines and ditches. This can accelerate the loss of nitrogen from agricultural lands to streams.

TMDL – Total Maximum Daily Load. An amount of a chemical/compound determined to be the maximum that can be discharged into an ecosystem without detrimental impacts.

Top-down Control – "The very large drive the very small;" Predation and grazing by higher trophic levels on lower trophic levels ultimately controls ecosystem function.

Trophic Level – "Trophic" means nutrition or growth, and wherein an organism derives its nutrition, its level. For example, an organism is a primary producer (plant) if it derives sustenance from nutrients and sunlight; an animal that eats plants (secondary producer or a primary consumer) eats other animals, which eat other animals (secondary consumer). These are all different trophic levels.

Turbidity – Reduced water clarity from increased sediment load into a water body.

Watershed – The area encompassing all the rivulets, streams, and rivers, etc. that drain into a water body. For example, the Chesapeake Bay watershed includes all the rivulets and streams and smaller rivers that flow into rivers, such as the Susquehanna, Patuxent, Potomac, Rappahannock, York, James, Chester, Choptank, Ninticoke, and Wicomico.

Water Column – Vertical section of the water from the surface to the substrate (bottom).
Water Table – The level of the underground water stored in rock.
Wetlands - Transitional habitats (whether natural or artificial, permanent or temporary) between dry land and deep water. They include marshes, swamps, peatlands, flood meadows, lakes and ponds, rivers and streams, estuaries and other coastal waters (e.g., salt marshes, mangroves and even coral reefs).
Zooplankton – Small, passively floating or drifting, animal-like organisms that live in the water.

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